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# Atlantic Coastal Studies

## Technical Report No. 19
## Part A

# *Recent Geomorphic History of Plum Island, Massachusetts and Adjacent Coasts*

by

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Part D. Caribbean Beach Rock Observations by Russell, R. J.

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# RECENT GEOMORPHIC HISTORY OF PLUM ISLAND, MASSACHUSETTS AND ADJACENT COASTS

by

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December 30, 1962

## ACKNOWLEDGEMENTS

This paper is part of an investigation of beach and coastal marsh development in the Plum Island area of New England. A reconnaissance study was made of the entire coast between Cape Ann and Kennebunk Beach, however, detailed investigation was limited to the Plum Island and Kennebunk Beach areas.

The study was made possible through financial support of the Geography Branch, Office of Naval Research, Contract Nonr 1575 (03) NR 388 002, with the Coastal Studies Institute of Louisiana State University. Dr. R. J. Russell. director of Coastal Studies Institute, visited Plum Island and has reviewed the manuscript. Dr. H. N. Fisk, of Humble Oil and Refining Company, read parts of the manuscript and contributed some valuable suggestions. The Exploration Department and the Geochemical Laboratory of Humble Oil and Refining Company made radiocarbon assays on peat and wood samples from the area which have been invaluable in determining relative changes of level. Cooperation of the Boston Office, U. S. Fish and Wildlife Commission, and Superintendents Gordon T. Nightingale and J. C. Apple of the Plum Island Refuge made it possible to work in the area. J. H. Hartshorn and E. A. Sammel, U.S. Geological Survey, Boston, Massachussets, were of much help in interpreting glacial features in the field. Drs. Chester Smith, University of Atlanta, Georgia, and R. C. Treadwell, Corpus Christi, Texas, assisted in the initial field session.

Dr. Ulrich Jux, Paleobotanist, University of Cologne, West Germany, analysed peat and sediment samples for floral and faunal content and conducted geochemical tests of peats. Through his techniques in paleoecology, environmental changes in the stratigraphic column were determined. Additional results of the paleoecological study will be forthcoming.

ABSTRACT

Plum Island and adjacent beaches are time-transgressive features which have formed during the past 11,000 years. The coast between Cape Ann, Massachusetts and Kennebunk Beach, Maine exhibits a morphological variety ranging from massive cliffed coasts to elongate straight beaches with intermediate types of crescentic beaches between rocky headlands. These shoreline contrasts are the result of a transgressive sea acting upon resistant bedrock in some sectors and unconsolidated Quaternary deposits in others. Along bedrock dominated portions of the coast, the shoreline is either cliffed or displays headland-crescent beach development with little Recent modification of coastal configuration. On the other hand, in coastal sections where unconsolidated Quaternary deposits are dominant broad and extensive Recent beaches have developed with resultant shoreline straightening.

Typically, the beaches are superficially separated from the mainland by shallow, salt marsh flats, or by shoal, estuarian water bodies. Both crescentric beaches between headlands and long, straight beaches are anchored on older mainland material at depths within the expected range of wave activity. Therefore, older mainland deposits, consisting primarily of glaciomarine clay, determine the position and alignment of modern beaches.

Relative changes of sea level during Recent times have affected shoreline positions and altered the source of sediments for beach development. For specific dating of sea level changes, the environmental boundaries between fresh and salt water dominance were established from ecological assemblages (floral and faunal) in the sediments, and these boundaries were radiocarbon dated. Resulting C-14 dates, mainly from _in situ_ peat deposits, provide several known positions of sea level at relatively specific times. Through this method, changing sea level position has been traced upslope to the present strand line.

The development of Plum Island Beach began prior to 6,300 years ago. At the time of its initiation sea level was lower than at present and the land was higher in elevation. The modern single-crested beach and associated dunes are the result of a transgressive sea eroding and redepositing Quaternary sediments along an unstable coast.

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# INTRODUCTION

The coast between Cape Ann, Massachusetts, and Kennebunk Beach, Maine,(Fig. 1) varies from massive cliffed coasts, bedrock headlands separated by crescent-shaped beaches, to comparatively long, straight beaches. These shoreline contrasts were developed as the result of transgressive sea activities against bedrock and unconsolidated Quaternary deposits. Between Great Boars Head and Israels Head, and in the Kennebunk Beach region, bedrock dominates the coast. Quaternary glacial deposits form only a thin veneer over bedrock and fill small valleys between coastal promontories. Along bedrock sections of the coast, the shoreline is either cliffed or displays headland and crescent-shaped beach development. Because of bedrock resistance to erosion, little recent modification of the shoreline has occurred along coasts where it dominates.

Plum Island and Wells Beach areas front basins where bedrock is relatively deep and glacial deposits are correspondingly thicker. The latter has supplied sediment that forms extensive beaches and dunes. The beaches of those areas extend for several miles but are interrupted by river mouths or marsh filled estuarine drainage outlets to the sea. Along sections of the coast where Quaternary deposits are dominant, their unconsolidated sediments are easily eroded and the shoreline has been straightened.

Salt to brackish marsh flats with associated tidal and estuarine water bodies separate the beaches physiographically from the mainland. Actually, the beaches are mainly anchored on bedrock or deposits of Quaternary "blue clay" (rock flour). Borings through beaches reveal that their bases lie about at limits of effective wave erosion.

Normal strandline processes have established beaches whose position and alignment are controlled by distribution of glacial sediments and older bedrock.

Plum Island and adjacent beaches originated when sea level was somewhat lower than at present and reached their current stage of development during Recent geologic time. Although the shore zone has shifted its position, beaches have been present for at least the past 6300 years.

Relative sea-land relations must be carefully considered for there has been (1) a period of continental rebound subsequent to retreat of continental glaciers, (2) general subsidence of the land at present and (3) eustatic rise of sea level accompanying ice melt. The story of relative sea level rise is revealed by weathered marine clay both above and below present sea level; a buried fresh water basal peat which follows up the slope of an underlying valley to the surface; and capping the basal peat, a seaward thickening wedge of salt water peat intercalated with layers of clay, silt and sand.

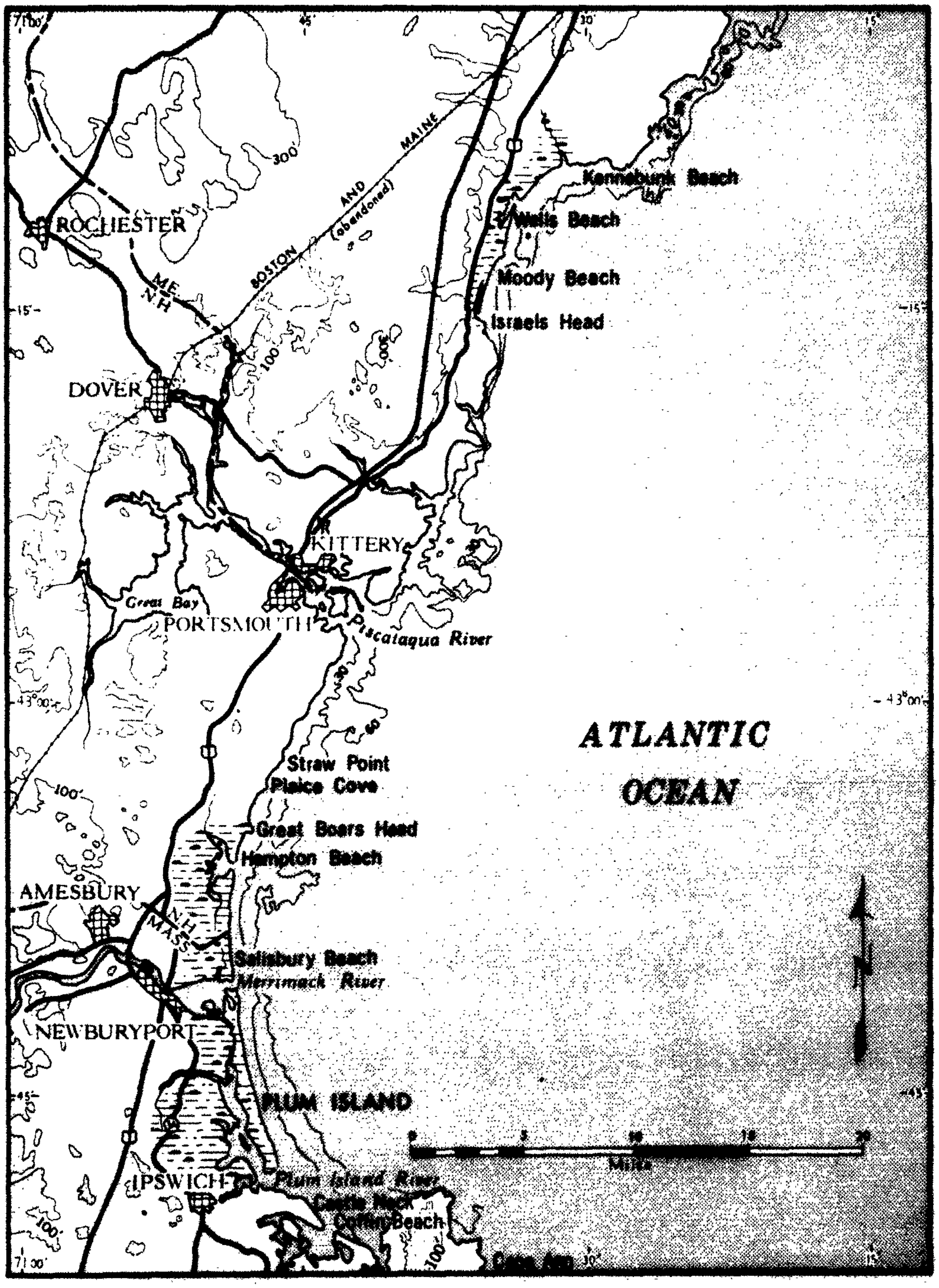


Fig. 1. Location map of the New England coast between Cape Ann, Mass., and Kennebunk Beach, Maine.

Floral, faunal and geochemical analyses indicate changes in environment from fresh to salt water. The fresh-salt water boundary establishes the level of the sea at any particular time, and by determining the boundary at several upslope points the relative rise of sea level can be followed as it drowned the coastal area initially. Time for upslope positions of sea level rise is established by radiocarbon dates on both fresh water peat and peat from the fresh-salt water boundary. From these data, rates of relative sea level rise are computed and an attempt is made to separate eustatic sea level change from effects of crustal movement.

## FACTORS AFFECTING BEACH DEVELOPMENT

The gross configuration of the shoreline between Cape Ann and Kennebunk Beach is bedrock controlled (Fig. 1). However, individual Recent beach deposits vary in position and alignment from regional bedrock trends. Glacial deposits filled pre-existing coastal valleys and have provided sedimentary material for modern beach construction. Cliffed and headland shorelines result directly from wave attack on mainland bedrock. Hydrographic charts of the area reveal highly irregular offshore bottoms adjacent to rock-dominated coasts. In general, submarine topography conforms with that of the adjacent mainland. The highly irregular sea floor reflecting predominantly bedrock, absence of a ready source of sediments, and contrasting composition of country rock allow little chance for an equilibrium to be reached between wave erosion, the sea floor, and the shoreline.

In contrast, areas with small crescent-shaped beaches between headlands and longer straight beaches bear testimony to the effectiveness of wave attack on unconsolidated Quaternary deposits. Glacial ice that advanced beyond the present shoreline for some unknown distance deposited quantities of till and outwash material. During late-glacial times glaciomarine deposits (locally called "blue clay") blenketed the area, the net result being the construction of a flat, gently sloping sea floor. Near-shore profiles from hydrographic charts show smooth, gentle offshore slopes seaward from both crescent-shaped and straight beach areas. A predominant, southward littoral drift has further modified nearshore hydrography through sand deposition in the Plum Island-Castle Neck region (Fig. 1).

Beaches are deposits which are physically anchored and stratigraphically positioned on older, underlying foundations. The position of a beach is determined by the location where the force of wave energy is spent on the slope of the sea floor. Equilibrium is attained between the base of wave erosion and the material and attitude of the foreshore zone. Erosion and deposition takes place near shore, while the balance is maintained between energy of the waves and the slope of the foreshore. Locally, wave energy can be expended either against glacial material *in situ* or on recently deposited nearshore sediment, depending upon sediment supply and sea floor relief. If there is an excess of sediment, either locally derived or from accumulation by littoral drift, deposition in the foreshore zone will exceed erosion rates. This results in beach progradation. If there is a deficiency of sediment, wave erosion on the foreshore will result in retrogression (retreat) of the shoreline. A continuing equilibrium between sediment supply and effects of wave erosion will maintain a stable beach.

In the Plum Island and Wells Beach areas, as well as in the smaller crescent-shaped beaches between headlands, the waves are attacking unconsolidated glacial material which erodes more or less uniformly. The position and alignment of the crescent-shaped and straight beaches reflect an equilibrium between the sea floor, wave base, and sediment supply.

## Bedrock

Bedrock is composed mainly of Paleozoic crystallines which have been complexly folded into steep-limbed, dominantly northeast-trending folds. Where the shoreline is essentially parallel to fold axes, the coast is simple and straight. In areas where the bedrock structure intersects the coast obliquely, valleys are embayed, while more resistant ridges project into the sea as headlands.

The general shape of the coastline is roughly arcuate, concave seaward, between bedrock promontories at Kennebunk Beach and the massive cliffs of Cape Ann. The coastal trend varies from approximately east-west in the Kennebunk Beach area to southeast from Plum Island to Coffin Beach, near Cape Ann.

Figures 2 through 4 are a series of strip maps which illustrate the significance of bedrock control on coastal configuration as well as the relationship between glacial deposits and beach location. At Kennebunk Beach (Fig. 2) bedrock promontories trend north-south, and arcuate pocket beaches, between the headlands, extend approximately east-west. Between Kennebunk Beach and Buckman Rocks, the bedrock topography is more subdued and obscured by Quaternary deposits. However, rock outcrops in the vicinity of Crescent Surf reveal its presence at relatively shallow depths. Southward from Buckman Rocks to Israels Head (Fig. 2) bedrock has not affected shoreline processes with the result that this coastal section displays a straight shoreline. From Israels Head to Straw Point, bedrock control of the coast is again more conspicuous, and cliffed and rock headlands dominate this section.

From Straw Point to Hampton Harbor a series of rock headlands fixes the major coastal trend in a south-southwesterly direction (Figs. 3-A and B). Between Hampton Harbor and the south end of Coffin Beach (Fig. 4-A and B, and Fig. 1) no bedrock is exposed along the shoreline which is composed of straight beaches. Bedrock outcrops form small islands in the marshes west of Seabrook, Salisbury and Plum Island beaches. In this area the bedrock is lower-lying and its buried surface plunges seaward. The massive bedrock core of Cape Ann rims the southern side of the basin.

Although the gross shape of the coastline is established by bedrock, the position and alignment of individual beaches vary from its general trend. For a distance of 20 miles the shoreline strikes across coastal marsh from bedrock at Hampton Harbor to bedrock at the south end of Coffin Beach and Cape Ann. Although interrupted by river mouths, each beach section is essentially straight. On a smaller scale the Wells Beach area shows a similar pattern of straight beaches and lower lying bedrock (Fig. 4). In these regions large amounts of unconsolidated Quaternary material have been deposited. At the seaward edge of Wells Beach and Plum Island the bedrock surface generally lies below the effective depth of basal wave erosion and exercises little effect on the position and alignment

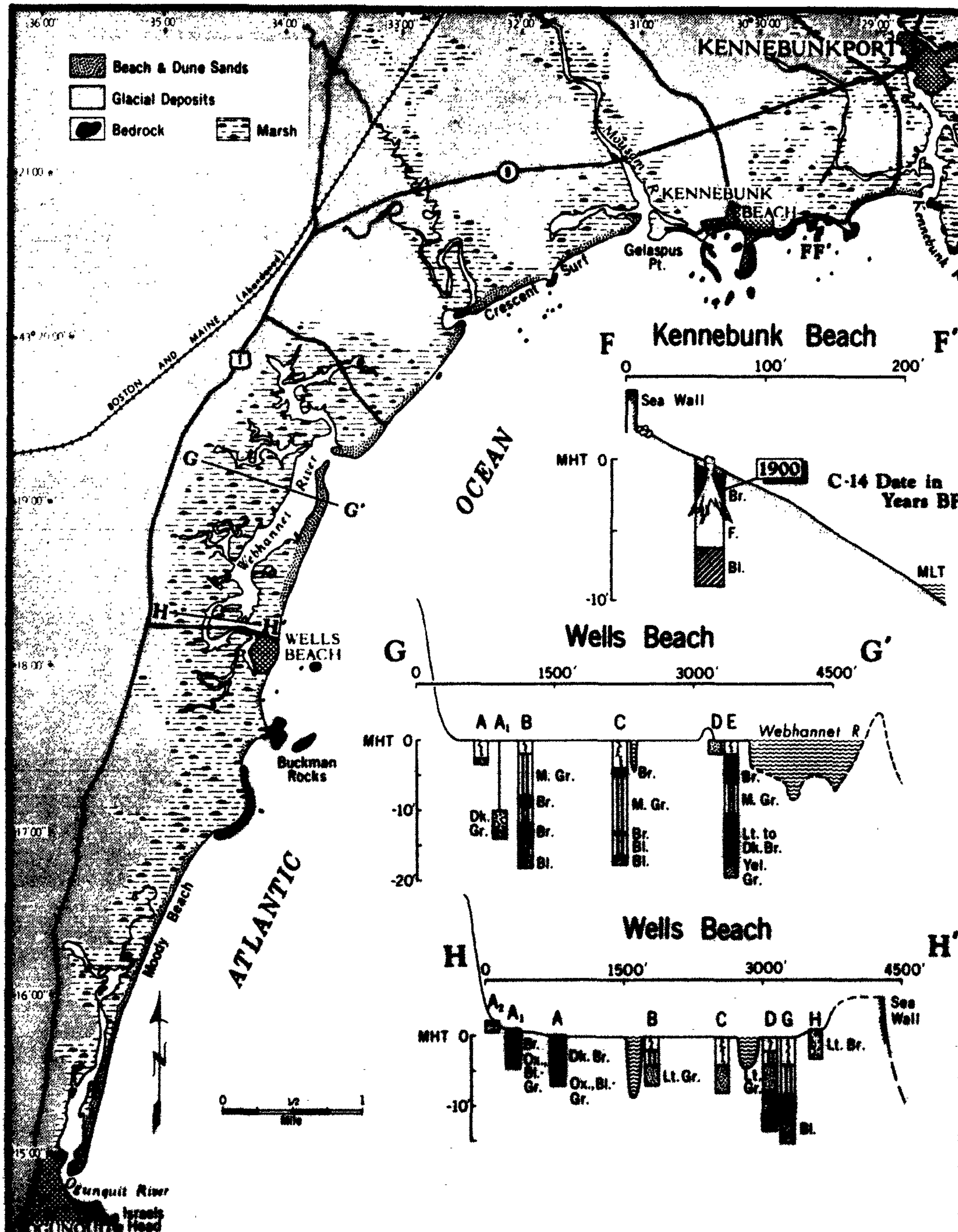


Fig. 2. Coastal Strip-Map and Cross-sections between Kennebunk River and Israels Head (modified from latest U.S.G.S. quadrangles).

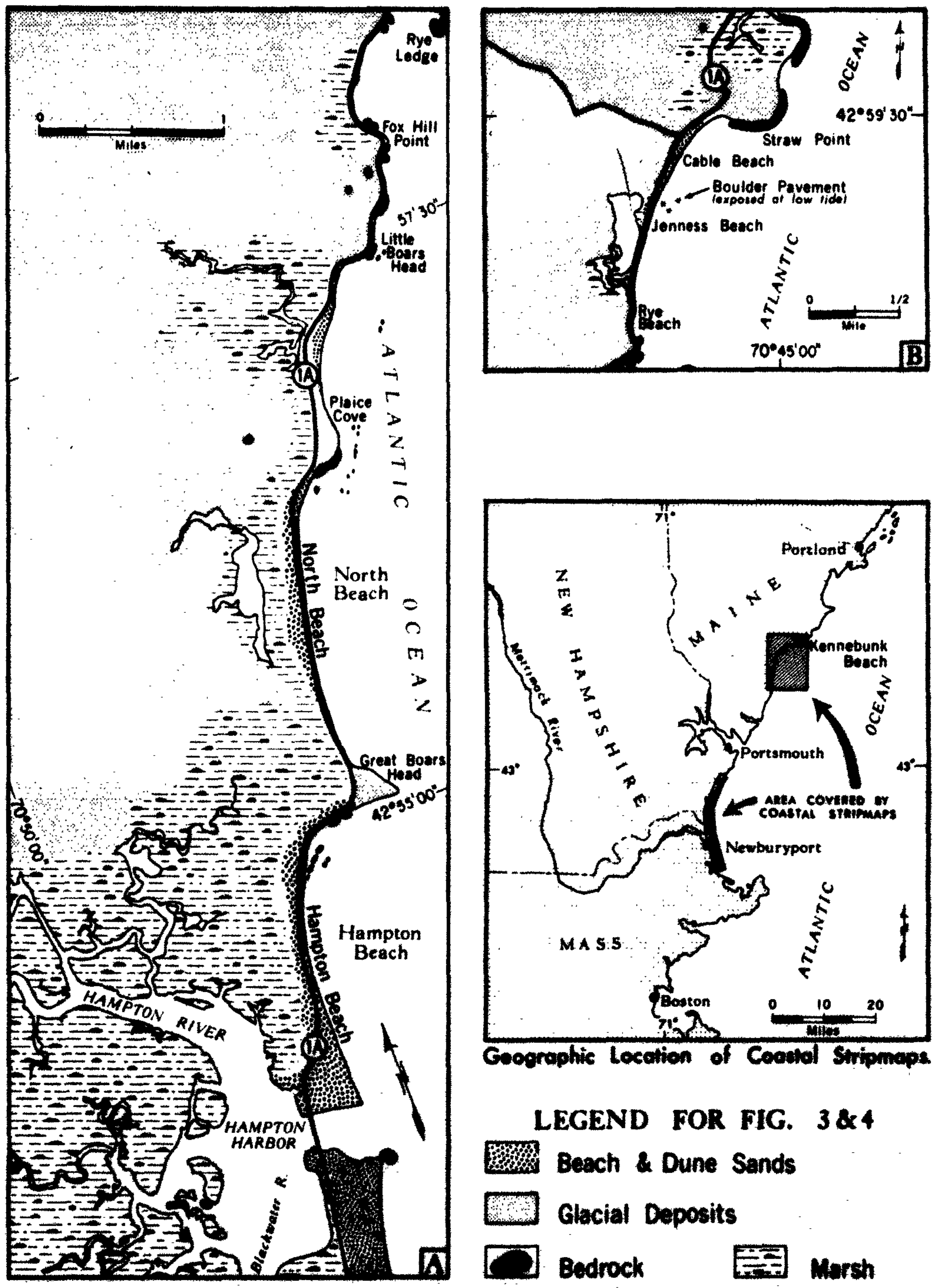


Fig. 3, A and B. Coastal strip maps from Straw Point to Hampton Harbor (modified from latest U.S.G.S. quadrangles).

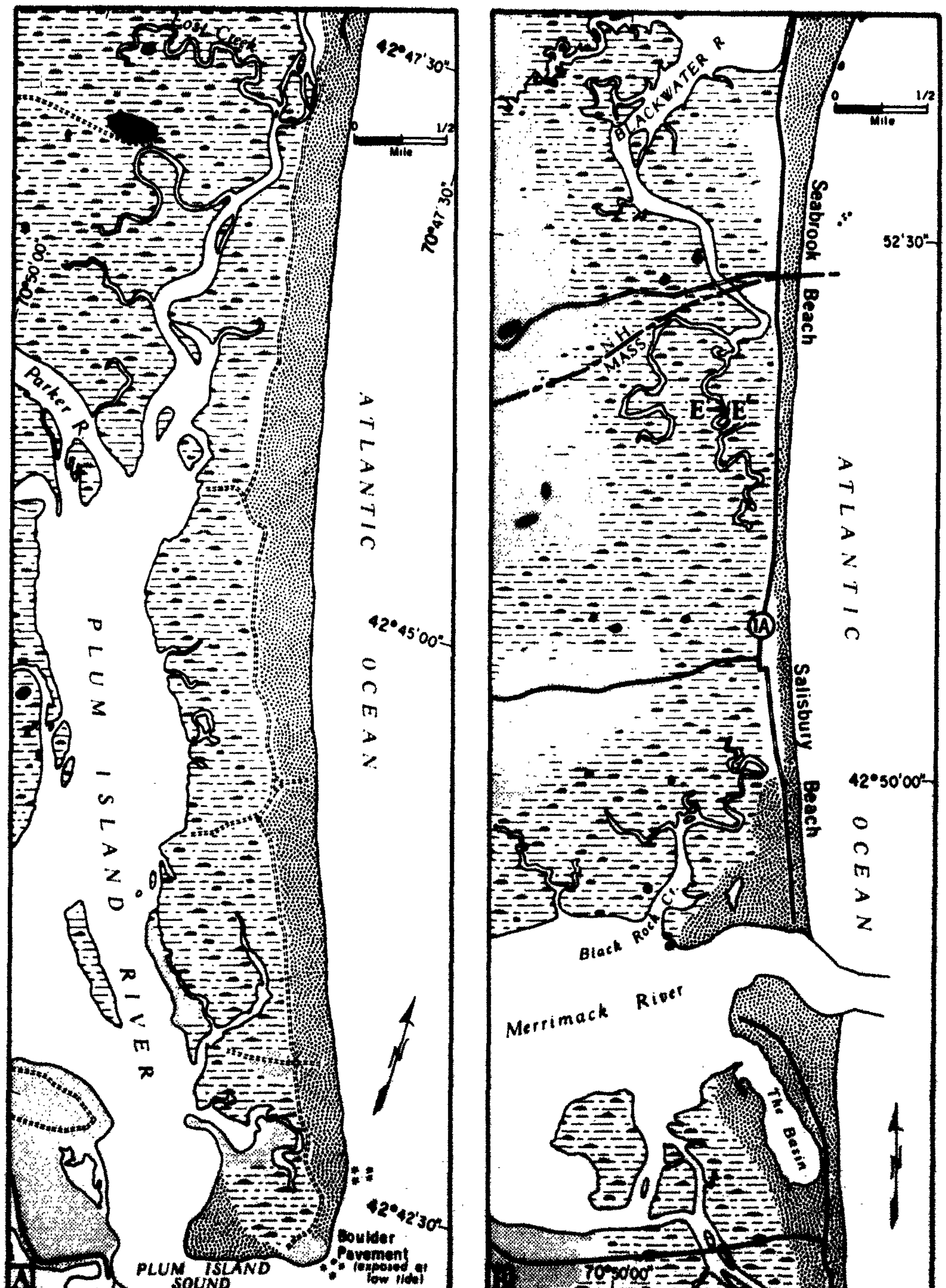


Fig. 4, A and B. Coastal strip-maps from Seabrook Beach to include Plum Island (modified from the latest U.S.G.S. quadrangles). Legend is indicated on Fig. 3.

of the shoreline. Secondly, even though the bedrock surface may be locally within the range of basal wave erosion, the bulk of unconsolidated sediments in the Wells Beach and Plum Island areas overshadows any direct effects of shoreline control by bedrock.

## Quaternary Deposits

Coastal New England was appreciably modified by moving continental ice during the Pleistocene. The number of ice advances in the Plum Island area is not known, but Kaye recognizes four and possibly five in the vicinity of Boston (p. B-73, 1961). The continental ice sheets scoured and shaped the resistant bedrock as well as leaving residual deposits of till throughout the area. In addition, glaciofluvial and glaciomarine sediments are abundant in the coastal zone.

The area covered by ice sheets during the height of glacial advances is likewise unknown, but it is apparent that they extended well beyond the present shoreline into the Atlantic Ocean. Till and outwash deposits are common within the coastal zone and a number of drumlins are present at or near the shoreline. However, in contrast to bedrock outcrops, drumlins do not form especially effective headlands.

A former drumlin, the "lost till mound" (Tuttle, p. 1216, 1960) occurs between Cable and Jennes Beaches (Fig. 3). It is now represented by boulder pavement in front of the beach. Apparently, this drumlin proved to be no major obstacle to shore processes because it lacked a bedrock core. Although till is also exposed midway along the beach, Cable and Jennes Beaches maintain a continuous, straight strandline.

The south end of Plum Island is dominated by a large drumlin (Fig. 4) which has a 30-foot sea cliff facing the ocean. Boulder pavement extends approximately 100 yards seaward from the cliff attesting to the effectiveness of wave attack. One half mile to the north, a similar massive boulder pavement is exposed at low tide. The boulders appear to be residue from a former drumlin which did not effectively hamper the slowly retreating shoreline. The boulders in both positions are exposed at low tide but are covered at high tide.

Along many beaches, such as Wells, Moody, Cable and Jennes, North, Hampton and Plum Island (Figs. 2, 3-B, 4-A) drumlins and other glacial deposits are exposed. Their presence signifies the importance of glacial deposits as a source of material for beach development. In addition, their seaward positions are clues to the underlying material on which beaches are anchored. Numerous borings reveal that glacial deposits are at shallow depths in the subsurface as well as being exposed in the vicinity of the strandline.

With the exception of Gelaspus Point (Fig. 2) and Great Boars Head (Fig. 3-A) all the headlands in the survey area consist of bedrock or drumlins with bedrock cores. Great Boars Head is mapped as a drumlin on all the geological maps of the area. It is approximately 40 feet high and forms one of the dominant coastal landmarks. No bedrock is observable in the wave-cut cliffs around the island but on the southwestern flank, low-lying Paleozoic bedrock is exposed along part of the beach (Fig. 4). It seems anamolous that the most prominant headland on the coast would be a drumlin without a bedrock core. Bedrock, near or slightly below sea level, may be suspected as being the major control of this prominant feature. Boulder rubble from artificial sea walls and residual boulders from the drumlin may mask the real reason for its seaward extension.

Although the Gelaspus Point drumlin does not reveal a bedrock core, its position on the easterly trending coast is protected from northeasterly waves. Residents in the area have erected sea walls which tend to inhibit local erosion.

The structurally and glacially formed depressions behind Plum Island and Wells Beach contain more extensive sedimentary deposits than do adjacent bedrock areas. (Distribution of glacial deposits are shown on Figure 2-4). The depression fronted by Plum Island is located near a drumlin field. Moreover, thick deposits of blue clay are present and separate the older till from Recent marsh and beach deposits.

From Great Boars Head northward to the Wells Beach area, glacial material is less abundant. Drumlins present form a relatively thin veneer of till over bedrock and valleys between headlands, although floored with glacial debris, are small in size when compared to the depressions behind Plum Island and Wells Beach.

<u>Blue Clay</u>

Late-glacial blue clay blankets much of the coastal region and forms a significant stratigraphic horizon. During late-glacial times large quantities of glaciomarine silt and clay filled estuarine and near-shore valleys and mantled flanks of bedrock and older glacial deposits. The clay forms an irregular belt which generally follows the configuration of the present coast. The seaward extent of blue clay deposition is unknown. Landward it has been mapped several miles inland, especially within estuarian valleys. The age of the clay in the Plum Island area is not known. Kaye (p. B-75, 1961) has identified three clays in the Boston area ranging in age from early Illinoian (?) to Tazwell substage in Middle Wisconsin. Oldale has mapped the clays on the Salem Quardrangle as late-glacial (p. C-60, 1961) and correlates them with the coastal clays of northeastern Massachusetts into Maine. The clays in the Plum Island area and northward to Kennebunk Beach, Maine, will be considered here as late-glacial in age, but the possibility that they may be older should be recognized.

In Boston the marine clay is present to about 30 feet above present sea level (Judson, p. 22, 1949; Kaye, B-75, 1961). Northward into Maine it is found at increasingly higher elevations (Tuttle, 1952 and 1960, and Bloom, 1959), however, it is possible that the clays are not all of the same age.

Clay not exposed to weathering is generally blue to gray in color but when weathered and oxidized the color ranges from yellows to buffs. (For a detailed description of the blue clay, see Tuttle, 1952; Bloom, 1959; Judson, 1949; Goldwait, 1953; Kaye, 1961 and Oldale, 1961.) Borings on the landward side of Plum Island revealed the easily recognised weathered clay surface at depths to 40 feet below present mean high tide. A few deeper borings farther seaward which encountered the clay revealed no evidence of weathering. Marine clay above the sea datum in the Plum Island area occurs at elevations of at least 20 feet.

Nature of the weathered clay in borings as well as exposures provides a clue for both direction and amounts of relative land-sea level change since its deposition. When released from its ice load the land uplifted more rapidly than eustatic sea level rise. A differential between levels of at least 60 feet resulted from the rapid rise of the land. The newly emerged sea floor exposed glacial till, outwash, and marine clays to erosion and weathering. Subsequently, part of the exposed belt was drowned by rising sea level. Easily identifiable glacial deposits form an excellent base from which to measure the thickness and development of Recent beaches and valley fill.

## Tides

As agents modifying local geology, tides, winds and currents have played a significant part. Semidiurnal tides are rather uniform along the New England coast. Minor tidal differences from place to place can usually be explained by contrasts in local configuration of the coast and degree of exposure to the open ocean. At the entrance to Merrimack River the mean tidal range is 8.0 feet and the spring range is 9.3 feet (U.S.A. Corps of Engineers, p. 22, 1953). The tidal ranges in Plum Island River at the south end of Plum Island (Fig. 4) are slightly greater, the mean range being 8.7 feet with a spring range of 9.9 feet. Tide gage comparisons with records from the Portsmouth Navy Yard Station show that an 8.0 foot mean tidal range is typical for that area.

More important to coastal changes and distribution of sediments is the frequency at which tides exceed mean high levels. Available records for the years 1927-1934, 1941, and from 1943 to 1951, show that average mean high water was exceeded by one foot some 107 times per year and by two feet some 12 times per year. Periods of cresting the mean high plane include the spring tides which would be approximately 20 percent of the total. The remaining tides which exceed the mean level are a result of storms. A one foot rise above high mean causes surface flooding of most of the coastal salt marshes.

Occasionally, Atlantic Ocean storms coincide with spring lunar tides and result in excessively high water and heavy destructive surf. In November, 1944, the plane of mean high tide was exceeded by 3.9 feet. Hurricanes, although infrequent, occasionally bring abnormally high water and winds. The effect of a hurricane on Plum Island Beach observed during the summer of 1954 showed temporary changes to the beach, but no long range study was made to determine whether or not there was permanent modification to the strandline. On August 31, 1954, the eye of Hurricane Carol entered the mainland over Long Island, New York, but continued northward, passing to the west of Worcester, Massachusetts. Consequently, hurricane generated waves expended their full energy on the coastal area in the Plum Island vicinity. Plum Island beach was visited the morning following the hurricane and the shape of the beach was greatly altered. High waves had destroyed the normal storm beach crest and back-wash had removed much of the foreshore section of the beach. The flat beach surface sloped from the foredune base to the water line. Reworked sand had been redeposited at the strandline to cause an overall widening of the beach. Pre-storm beach profiles compared with those on the third day following the hurricane reveal changes as shown on Figure 5-A. Although the beach had been partially restored by the time of the resurvey, the strandline still extended 5 feet seaward of its pre-storm position. A small berm had begun to reform, but much of the flat beach surface still existed.

New England beaches are constructed to conform with high tide level while dunes form appreciably higher elevations. Storm generated waves are usually incapable of topping the dune ridge and thus affect mainly the foreshore section of the beach. Principal result of storm wave erosion is removal of foreshore beach sand which is either deposited offshore, drifted along shore, or carried into estuarian river mouths. Following a storm, offshore sediments are eventually reworked back onto the beaches where the adjustments between shore processes and sediment supply gradually attain pre-storm equilibrium. Much of the sediment transported into the estuarine rivers during abnormally high tides will eventually be transported to the sea by ebb flow and again become available for beach deposits.

## Winds

Winds are primarily responsible for producing ocean waves and currents, therefore, the direction of wave approach and resultant littoral currents are dependent upon wind direction. Wind roses from U. S. Weather Bureau observations covering a nine-year period showed prevailing winds from westerly quadrants. The greatest frequency of the westerly winds is from the northwest and winds with greatest duration are from the southwest. Since westerly, or offshore winds tend to dampen wave energy they do not appreciably affect the coast.

Because of the trend and configuration of the coastline from Kennebunk Beach to Cape Ann, most significant onshore winds come primarily from the easterly quadrant. Northeast winds show a slightly greater duration and velocity than winds from the southeast. Although southerly winds are comparable in duration to southeast winds, Cape Ann protects most of the coast except the Kennebunk Beach area from their effects.

Winds of gale force from the easterly quadrant constitute about 70 per cent of the storm winds. The most frequent and severe gales approach the coast from the northeast. A summary of gales

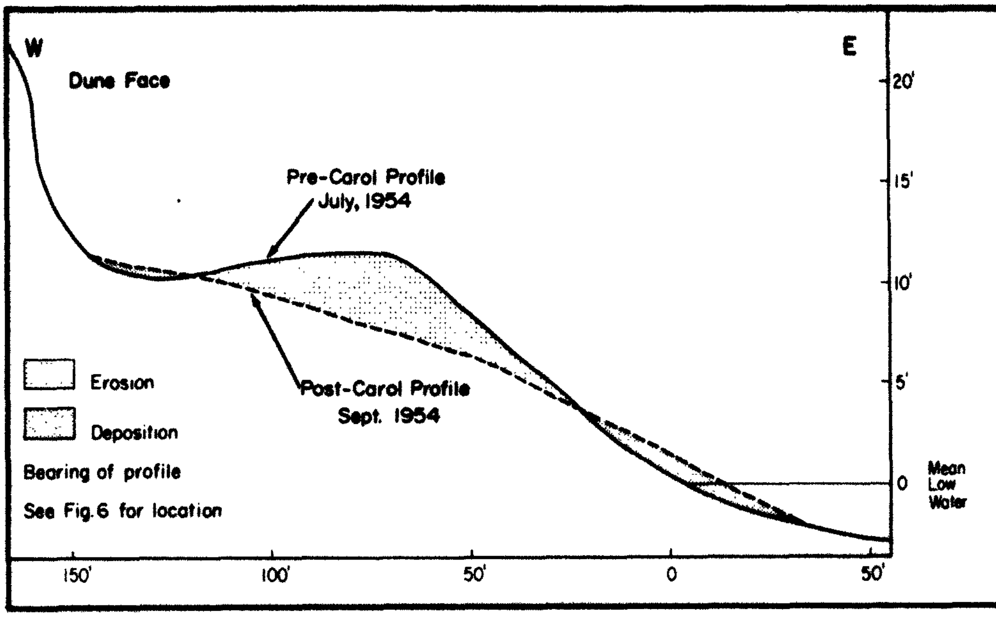


Fig. 5-A. Profile of Plum Island Beach before and after hurricane ~~Carla~~, 1954 (location of profile on inset map Fig. 6).
Carol

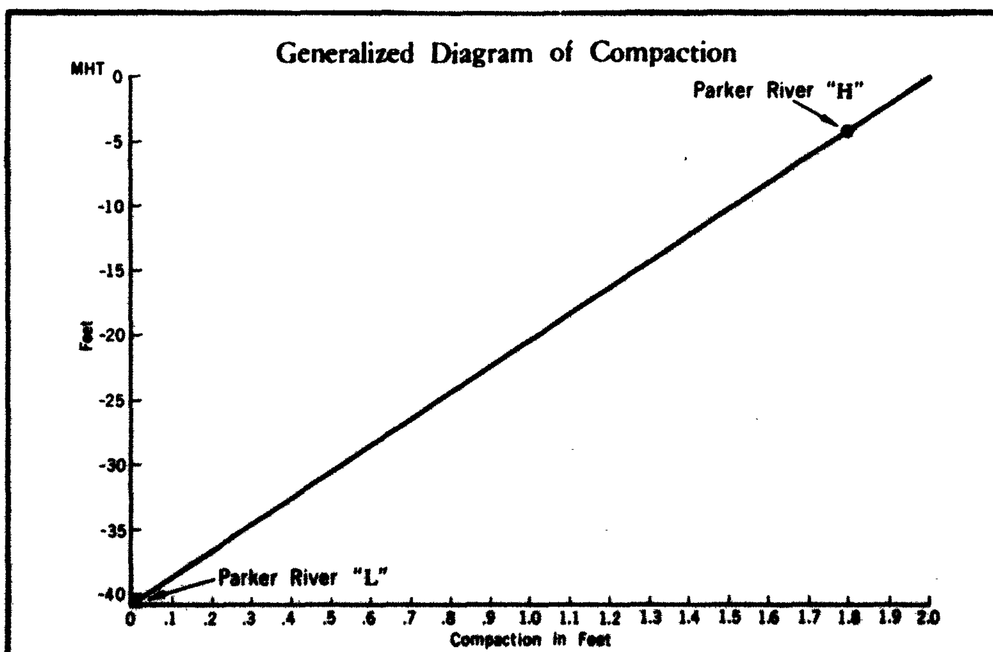


Fig. 5-B. Compaction diagram determined from Parker River borings H and L in the Plum Island Marsh (location of borings on Fig. 6).

compiled by the U. S. Weather Bureau, Boston, Massachusetts revealed that during a 75 year period, between the years 1870-1945, 160 gales occurred. Of these 50 per cent came from the northeast and a total of 67 per cent from easterly quadrants. The storm period which causes the greatest amount of erosion and shore damage occurs during the winter months from November through March. Swell diagrams show medium to high swells with a predominantly north-eastern approach.

An effect of the easterly winds is indicated by extensive beach dunes in the Plum Island to Coffin Beach area. Many of the dunes rise 30 or more feet in elevation above sea level. The easterly winds are gradually extending the dunal belt westward over the adjacent marsh. The dominant forms are parabolic, crescentic, and occasionally longitudinal dunes which are all oriented to the onshore easterly winds. Deep blowout and wind channels form valleys oriented at right angles to the shoreline. Since the dominant winds and storms which affect the coast come from the northeast, the resultant wave direction is toward the southwest. This wind and wave direction produces littoral currents with a southerly component which is responsible for a southerly beach drift.

Currents

The effect of littoral currents is to transport coastal sediments from north to south. However, in the area between Kennebunk Beach and Cape Ann the pattern of the littoral drift is complicated. North of Great Boars Head there is no evidence which shows a dominant drift either north or south (Tuttle, p. 1217,1960). It appears that no drifting of sediments occur around the headlands from one beach to the next. This can be partly explained by the dominance of bedrock and relative paucity of glacial material north of Great Boars Head. The seaward projecting headlands protect the beaches and disrupt any littoral current which might develop close to the shore. From Kennebunk Beach northward the coastal trend extends more easterly and protects the Wells Beach basin and the area some distance southward from waves motivated by northeast winds.

South of Great Boars Head north-to-south drift appears to be well developed. Current measurement by floats and computations from tidal range and river discharge by the U. S. Army Corps of Engineers reveal the nature of the complicated tidal and littoral currents. Float observations were made from August to November in 1932 from Great Boars Head to Seabrook Beach. These observations indicated that inlet tidal currents predominated over wind and littoral currents, but that this predominance decreased rapidly as distance from the inlet increased. The floats, which were not subject to the effects of the inlet, had average southward velocities varying from 0.03 to 0.45 feet per second and maximum velocities varying from 0.08 to 1.67 feet per second.

Current measurements by floats were made off Salisbury beach in 1931 where they averaged 0.07 to 0.40 feet per second and attained maximums of 0.08 to 0.70 feet per second. These were a combination of littoral and tidal currents and moved south toward the Merrimack on flood tide and away from the river in various directions at ebb tide (U. S. Eng. 1953, p. 7 and 8).

Lateral variation of grain size on Plum Island indicates a slight predominance of a southerly littoral drift. Grain size is coarsest at the mouth of the Merrimack River and becomes progressively finer toward the south end of the island. Dune sediments also show a similar grain size trend.

The extensive accumulation of dune sand from the Merrimack River to Coffin Beach increases southward in height and width. On the southwest end of Plum Island a sand apron is extending into Plum Island River and dunes are forming on the sand flats. Offshore profile between the mouth of the Merrimack River and Cape Ann shows a southward flattening and the 30 to 60-foot offshore contours (Fig. 1) extend progressively farther seaward.

The source of drift sand appears to be from the sea floor, from coastal erosion north to Great Boars Head and from the Merrimack River. Although the Merrimack River is estuarine for several miles inland from the coast it apparently contributes sand to the adjacent sea floor. Both ebb and flood tidal currents near the mouth of the Merrimack reach speeds in excess of those necessary for sand transport.

Mean currents for a portion of the Merrimack River at the south jetty were computed in 1938 (U. S. Army, Corp. of Engineers, 1953). With a tidal range of 9.13 feet and a fresh water flow of 4660 cu. ft./ sec. flood tides obtained velocities of 2.58 ft./sec. while ebb flow reaches 3.23 feet. River ebb currents measured between the jetties of the Merrimack in November 1937 were even greater, exceeding 6.0 ft./sec. and with maximum currents of 6.5 feet. Our tidal current studies made during this project in Lost Creek (Fig. 4-A) show that medium-sized sand particles began to move by saltation at velocities of 0.70 to 0.80 ft./sec. Before velocities of 1.0 ft./sec. were attained, suspended material increased the turbidity so much that individual sand particles could no longer be followed. The high velocities for both the flood and ebb tidal current in the Merrimack River estuary appear to be adequate to transport sediment. Occasionally high spring tides coincide with rising river stages and easterly storms. During such occurrences extreme current velocities result.

It is probable that during normal ebb and flood tidal conditions little sediment may actually reach the sea from the mainland. However, during easterly storms and spring tides, tidal currents extend their influence farther inland and upset the equilibrium between normal tidal flow and estuarine bottom sediments. The occurrence of storms and high tides coinciding with high stages in the Merrimack River would produce above-normal ebb-current velocities and result in transporting sediments to the sea.

# BEACHES

Beaches exist along the coast of the survey area wherever glacial deposits are present in sufficient quantities to supply sediments for their development. They form single, crescentic ridges between closely spaced headlands and straight beaches which span the larger depressions between widely spaced rock promontories. Dunes have developed where glacial deposits are abundant or where sand is added to down-drift areas of a beach. No multiple accretion beach ridges are present along the entire coast. Landward drift of sand, contemporaneous with dune building, has widened the dunal belt and sand is encroaching on the adjacent marsh. Typically, the beaches are superficially separated from the mainland by salt marsh and estuarian water bodies. Even the beaches in valleys between closely spaced headlands have marsh on their landward side. Where sand is deficient stony or boulder debris accumulates as beach deposits.

The azimuth of the beach strike extends from east-west at Kennebunk Beach, to southwest from Israels Head to Great Boars Head, to southeast from Hampton Harbor to Coffin Beach. Some individual beaches in New Hampshire vary from this trend (Tuttle, 1960). Because of the wide range of beach alignments, wave processes do not wholly explain their orientation. The gross configuration of the shoreline is fixed by bedrock outcrops but the position and alignment of individual beaches is largely a result of wave attack upon a shelf of unconsolidated Quaternary deposits. Beaches are anchored on older mainland material at a depth within the basal limits of wave erosion. Borings through the beaches and adjacent marshes reveal the nature of underlying material. On some beaches glacial deposits are exposed above sea level and the beaches are morphologically tombolos. The significant clue which both the borings and the exposed till on beaches reveal is that glacial material extended offshore, forming the shelf over which the sea transgressed and on which beaches were formed.

## Position and Alignment

In the Kennebunk Beach area the bedrock strikes north-south and a series of east-west trending beaches lie between bedrock headlands (Fig. 2). The beaches are crescent-shaped and join the rock headlands at each end. The largest accumulation of sand is normally near the center of the crescent and thins out to a veneer where beach-ends join the headlands. Sand is generally deficient in the Kennebunk area. Much of the glacial till originally deposited over bedrock at shallow depths has been lost to marine erosion. Gelaspus Point is one of the few remaining drumlins along the present strandline.

Borings through the beaches in the area of Kennebunk show that they are resting on clay at shallow depths. Kennebunk Beach is typical for the immediate area. On Figure 2, the Section (F-F') shows a thin layer of beach sand overlying peat, glacial sand and weathered clay at the bottom. The clay surface was reached at 7 feet below mean high tide. The same clay is exposed at low tide as a step at the base of the beach front.

From Gelaspus Point southward, including Moody Beach, (Fig. 2), beach alignment changes from east-west to southwest in direction. Individual beaches between river mouths are straight. In this depression glacial deposits are more abundant and bedrock control for individual beaches is not important except for the small crescent-shaped beach between rock headlands south of Buckman Rocks. This section of the coast is protected from the effects of the northeasterly winds and resultant waves and the net effect of along shore drift is not dominant in either direction. Approximately 1.5 miles of estuarine tidal channels and salt marsh separate the north end of Wells Beach from the mainland. The extension of mainland glacial deposits beneath overlying marsh and beaches to the sea floor is shown by borings through the marsh and the presence of till outcrops on the beaches. Beach position and alignment is correlative with the underlying material on which it is anchored.

At Wells Beach two shallow cross-sections (Fig. 2, G-G' and H-H') were made across the marsh basin to the beach from G to G'. A cross-section of the subsurface glacial valley of the Webhannet River is shown. The borings generally were bottomed in blue clay, with till toward the mainland. Borings through beach sand were not possible with hand drilling equipment, but the approximate depth to clay beneath the beaches is suggested by the seaward deepening of the clay surface in section G-G'.

Section H-H' reveals glacial deposits at shallow depth which terminate near the coast in till. The clay was reached in borings A', A, D and G in this cross-section. In addition to the sections, exploratory probes were made in the marsh adjacent to Wells Beach, Moody Beach, and the beach on the north side of the Webhannet River outlet. Blue clay or till was present in each of the tests at depths of less than 15 feet below mean high tide level.

Wells Beach town is partly located on till and the shoreline here is slightly convex toward the sea. This may result from a residual headland or possibly only the effects of sea walls which protect this portion of the beach. Bedrock is located offshore only a short distance and it may extend landward at shallow depths beneath Wells Beach and might cause this small irregularity of the strandline.

The coastal trend from Israels Head to Hampton Harbor is southwest (Fig. 1). However, some of the individual beaches in New Hampshire vary slightly from this direction (Fig. 3). Test borings in the marshland west of the beaches in Figure 3 were all bottomed in clay or till at depths of less than 20 feet below the datum. Till exposures are present on Cable and Jennes Beaches and on Rye and North Beaches. These provide further evidence that glacial deposits underlie the adjoining beaches.

By comparing Figures 3 and 2 the contrasts are evident between the headland-beach type where rock promontories are closely spaced and straight beaches where rock promontories are more widely spaced. Glacial deposits <u>in situ</u> are the source material for beach deposits in both cases.

The crescent-shaped beaches show the result of differential erosion between unconsolidated deposits and bedrock more sharply than along shorelines where bedrock outcrops are widely separated. Kennebunk Beach, the beach south of Buckman Rocks, and the crescent-shaped beaches between Fox Hill Point and Little Boars Head are typical examples of beaches between closely-spaced headlands. The short distance between headlands limits the radius of curvature of the beach.

Waves entering the pocket between the headlands are refracted to points around the circumference of the arc. Because the unconsolidated sediments between the headlands are more exposed to direct wave attack, the greatest amount of shoreline retreat occurs in the central area. From the arc center, the force of the waves diminish toward the headlands establishing the shape of the strandline. The largest sand accumulation is located near the arc center where wave erosion is greatest. In addition, sand is added to the central area by in-drift from the beach ends toward the arc center.

As the distance between headlands widens and exposes more shoreline to direct wave attack, the radius of curvature of the beach increases. Between Straw Point and Rye Beach the beaches are essentially straight except where their ends join the headlands. From Little Boars Head to Plaice Cove, North and Hampton Beaches become straighter as the distance between headlands is increased. Longer sections of the shoreline where bedrock is virtually absent is shown on Figures 2 and 4. The series of beaches between Kennebunk Beach to Buckman Rocks and Moody Beach are straight. A slight promontory in the center of Crescent Surf interrupts straight beaches on either side. The longest span of shoreline where bedrock is absent and glacial deposits predominate is from Hampton Harbor to Coffin Beach. For a distance of approximately 20 miles the beaches between river mouths are straight, however, the trend of beach alignment changes from southwest to southeast.

Borings through the marsh adjacent to the Hampton, Seabrook and Salisbury Beaches encountered either bedrock or blue clay at depths of less than 20 feet. Several borings were made through the beach and dunes of Plum Island which reveal the nature of the island and the material on which it is resting (Fig 5) The three test holes (Profiles A-"Q", B-"M" and "Y") made on the beach front at approximately mid-tide level were bottomed in glacial clay. In boring "Y" clay was reached at a depth of 57 feet below the datum. This boring appears to be located over a topographic "low" in the eroded clay surface. It is possible that a former outlet to the sea extended through Plum Island in this area. Glacial till outcrops in the dunes a short distance to the south, and to the north the clay surface shallows to 33 feet. Boring Q in the Rowley River line bottomed in clay at 33 feet below mean high tide level and it was reached at 43 feet below the datum in Boring M of the Parker River line. Three additional borings, J, K, and L, along the Parker River section, were made on the back slope of the dunal belt to the marsh contact. Clay was reached between 41 and 43 feet in each of these borings. Toward the north end of the island between the highway to the mainland and the Basin (Fig. 4) clay was reported to be approximately 18 feet below the datum (water well information).

In borings to the clay surface, the presence of a drumlin and till toward the south end of Plum Island, and an offshore boulder platform which is the residue of a former drumlin is evidence for the type of material which underlies and extends offshore from Plum Island. In effect, Plum Island is anchored on glacial deposits. Although no detailed study was made of Castle Neck and Coffin Beach (Fig. 1) drumlins and other glacial material are known to be present on those beaches.

## Summary

The gross outline and configuration of the coast between Kennebunk Beach and Cape Ann is controlled by bedrock. However, individual beaches vary from bedrock trends. Beach position and alignment is a direct product of the distribution of glacial deposits and wave processes. Onshore winds and resultant waves come mainly from the easterly quadrant with greater velocities and duration from the northeast. The waves are reinforced by diurnal tides with a range of about 8 feet. Southward flowing littoral currents are set in motion by the northeast winds and waves. Littoral currents have added sediments to Plum Island, Castle Neck, and Coffin Beach, and they are areas of extensive sand accumulation and dunal development.

Since beach position and alignment ranges from east-west at Kennebunk Beach to southeast from Plum Island to Coffin Beach, factors other than waves are responsible for beach location and orientation. Both the crescent-shaped beaches and the longer straight beaches are mainly anchored on glacial deposits of blue clay or till. The beach anchor is revealed by borings through the Recent deposits or indicated by the presence of glacial till exposed in the beaches. The presence of till and clay beneath the beaches and exposed along the beach trend is evidence that these deposits also extend offshore to the sea floor. It was over and against these deposits that the sea transgressed.

It is significant that most of the beaches in the survey area are anchored on glacial deposits at depths, except in local topographic "lows", well within the expected range of the effects of wave erosion. As a general figure, Russell (p. 596, 1958) considers the critical depth of effective wave erosion under normal conditions to be less than 30 feet below low mean tide. That the beaches only superficially are separated from the mainland by shallow coastal marshes and shoal estuarine drainage systems is evident from the borings in the coastal zone and the presence of till along the strandline. An "offshore" location has little relevance to their origin, position, and alignment. They are anchored on mainland material.

The crescent-shaped beaches between headlands are formed by the differential effect of wave erosion around the circumference of the restricted basin. The greatest effect from wave erosion, depending on wind direction, is approximately midway between the headlands.

Here the shoreline has retreated the fartherest inland and the largest accumulation of sand is present. Upon entering the basins waves are refracted in a radial pattern to all sides of the circumference of the basin. Refracted waves diminish in power and the effects of wave erosion against the foreshore floor decreases from the arc center toward the ends of the beach. Likewise beach sands decrease in quantity toward beach ends which overlap glacial deposits or bedrock.

Straight beaches result along coastal areas wherever unconsolidated glacial deposits are exposed to wave attack over relatively long distances between bedrock exposures. From studies made in both the Atlantic and Gulf Coasts, Russell has observed that all straight beaches are located along coasts of unconsolidated rocks (Russell, p. 596, 1958). "What all long, straight beach localities have in common is relatively unconsolidated rock exposed to wave action; Tertiary or Quaternary rocks along most of the Atlantic coast, glacial deposits north of New Jersey." In the Wells and Plum Island areas glacial deposits predominate and beaches are straight.

## RELATIVE CHANGES OF LEVEL

Recent sea level rise has been a subject of geological discussions for many years, but the problem of quantifying effects of the several processes responsible for relative movements of land and sea still exists. Literature emphasizes effects relating to postulated climatic change and crustal movement. Local compaction of sediments, another process affecting relative movement, should be considered, especially in soft, uncompacted, water saturated Recent sediments.

The New England coast has apparently reversed its vertical direction of movement since glacial times (Newman and Fairbridge, p. 115 A, 1961; Redfield and Rubin, 1962). Following glacial retreat the land initially rebounded but is now thought to be subsiding. Whether land rebounded or subsided, the sea was rising eustatically at a rate less than crustal movement. To quantify amounts and rates of sea level rise, to prove or disprove a higher-than-present hypsithermal sea stand during Recent times, and to determine when the sea reached its present position, it is necessary to ascertain the processes involved and to determine the intensity at which each is operative along a segment of coast. To explain the total relative movement, it is necessary to evaluate amounts of crustal warping, eustatic sea changes, and effects of local compaction. If the New England coast were tectonically stable the problem would be considerably simplified.

The crucial requirement for deciphering processes causing relative land-sea movement is establishment of the time when the sea reached its present stand. Had it continued to rise throughout Recent time, it would be impossible to separate isostatic from eustatic processes. However, it appearsthat a eustatic stillstand was attained long enough ago to be recorded in the stratigraphic column. Our present dating and ecological techniques provide a rather good approximation of the date. An increasing amount of evidence from different parts of the world indicates the sea reached its present stand from 3000 to 5000 years ago with only minor changes since that time (Fisk, 1952; Russell, 1957; Fisk and McFarlan, 1955; LeBlanc and Bernard, 1954; Gould and McFarlan, 1959; McFarlan, 1961; Godwin, Sugate and Willis, 1958). Once the position of the sea stand is known, any subsequent change of level in the Plum Island area would be attributable to crustal lowering. Conversely, land-sea movement prior to the time of eustatic stillstand resulted from both eustatic sea level rise and crustal downwarping. The rate at which changes of level occurred was then faster. If the rate of crustal downwarping remained constant during the period of Recent subsidence, the amount of sea rise is indicated by a comparison of movement rates before and after the sea stillstand.

A rate of compaction estimate is made by determining the rate of subsidence from points near the marsh surface. The difference between the amount of subsidence for a near surface sample and the post eustatic stillstand rate is primarily the result of compaction. Once this amount is established it can be applied to the sediments deposited prior to the eustatic stillstand.

The New England coast is structurally unstable and is not an ideal laboratory from which to get a clear picture of the processes involved in relative movements. However, through the use of radiocarbon assays and ecological studies, data have been obtained which make possible the establishment of a number of relative sea-land relationships during Recent times. Changing rates of movement provide clues that indicate approximately when the sea reached its present stand.

Paleozoic bedrock, deposits of glacial till, outwash, and clay, all form a firm basement to which relative sea level changes can be referred during Recent times. To obtain specific data on sea level changes in the Plum Island marsh, six borings, whose relative positions are shown on the diagramatic illustration, Figure 7-II, were used. Five of the borings are bottomed in glacial clay or bedrock which virtually eliminates the factor of sedimentary compaction which would affect the vertical position of the dated peat, whereas the sixth (Parker River H) is a shallow boring purposely positioned over the deepest part of the Recent fill, where maximum compaction of underlying Recent sediments should be registered. Detailed floral and faunal studies were made from sediment and peat samples taken from borings A, B, H and L of the Parker River section to determine environmental changes during Recent deposition. For time control, radiocarbon dates were determined from fresh marsh peat recovered from the glacial-Recent boundary in five borings along the valley slope (A, C, B "a", K and L), and at two positions along the fresh-salt marsh interface (B"b" and L). The valley profile in Figure 7-II is diagramatic since two borings from the Stackyard Road section (Fig. 6) (Stackyard Road K and C) were included for additional reference points up the valley slope. The relative seaward position of the Stackyard Road section and its proximity to the Parker River line justifies the use of the two borings in the correlation. Three radiocarbon dates were also determined from peat samples at different levels in Parker River B boring (B"a", B"b" and B"c").

Although glacial deposits are still undergoing lithification at some minimal rate, their proximity to bedrock, the short duration of time, and relatively great thickness of overburden that has been deposited on them are such that the present compaction rate of these older materials is negligible and therefore has been disregarded. Any rise of the sea along the upslope interface between glacial and Recent deposits is primarily the result of eustatic sea level changes, of regional crustal movement, or a combination of both.

## Crustal Movement and Eustatic Sea Level Changes

Ecological studies in the Plum Island marsh reveal the story of a Recent sea rising and transgressing a structurally and glacially formed valley system. Two distinctive peat horizons indicate changes that resulted from the transgression. A dark brown to black peat, derived from a mixed assemblage of trees and fresh water plants, caps the glacial deposits. This fresh water peat layer of varying thickness continues up the valley slope to become contiguous with modern fresh water marsh plants which now grow slightly above high tide level. Overlying the fresh marsh peat is a seaward thickening wedge of inorganic sediments and brown peat that has been derived from salt marsh vegetation. Borings reveal a continuous development of brown, salt marsh peat from a depth as great as 40 feet to the surface. The development of salt marsh peat is not continuous in any single boring, but it is present in each boring so that a record is preserved indicating that marsh growth kept pace with the rising sea. The peat layer is present nearly everywhere within the upper 12 feet of marsh, but below this depth it is encountered less frequently in borings toward the coast. In general, both fresh and salt marsh peat kept pace with the rising sea, but below the 12 foot level clay, silt, and sand incorporating marine and brackish shells dominate the seaward part of the wedge of sediments. This suggests better connections with open water prior to the time of deposition of the upper 12 foot layer. This could reflect more rapid crustal downwarping, less rapid sedimentation, or more likely, significant eustatic sea level rise prior to that time.

The two contrasting peat layers furnish significant clues to both marsh development and sea level changes. Fresh marsh plants that formed the lower peat now thrive above high tidal influence and suggest a rising water table that kept pace with the rising sea. This is clearly shown when the dates for borings A and H are compared. Although there is only one foot depth difference in the two borings below the present marsh surface, there is some 1800 years differential in time. Part of this difference results from local compaction of sediment and part from contrasting depositional histories between the two points, but there is also a reflection in age variance between the development of fresh marsh and salt marsh peat. A time differential between the development of fresh marsh peat and the overlying salt marsh peat is also illustrated in boring B by comparing dates B"a" and B"b". The 3625 years BP date marks the absolute time of sea invasion over this point as established from ecological studies, and is 600 years younger than the basal fresh marsh peat. Radiocarbon dates for the fresh marsh peat merely reveal the time of growth of plants that lived before the sea invasion. A decreasing rate of sea level rise, or a minor pause, could result in a considerable time-lapse between the development of fresh marsh peat and the absolute time of sea invasion shown by the fresh-salt water boundary. Radiocarbon dates on the basal fresh marsh peat may indicate dates considerably older than the absolute time of the sea invasion. Thus the only significant dates in fresh marsh peat are those from contacts at its base and top.

When time intervals and vertical distances are considered between upslope points on basal fresh marsh peat, a maximum age is indicated for sea level rise and/or changes in rates of movement. The radiocarbon dates on the basal peat show a time transgressive history for the past 6280 years. Because of the relatively thin layer of fresh marsh basal peat in Parker River L, the date 6280 years B.P. approximates the age of both the lower peat and the fresh-salt water interface. The basal peats lie either on glacial debris or bedrock which are relatively unaffected by compaction, hence their inundation was caused either by crustal warping or eustatic sea level changes. When the amount of total subsidence per century for the

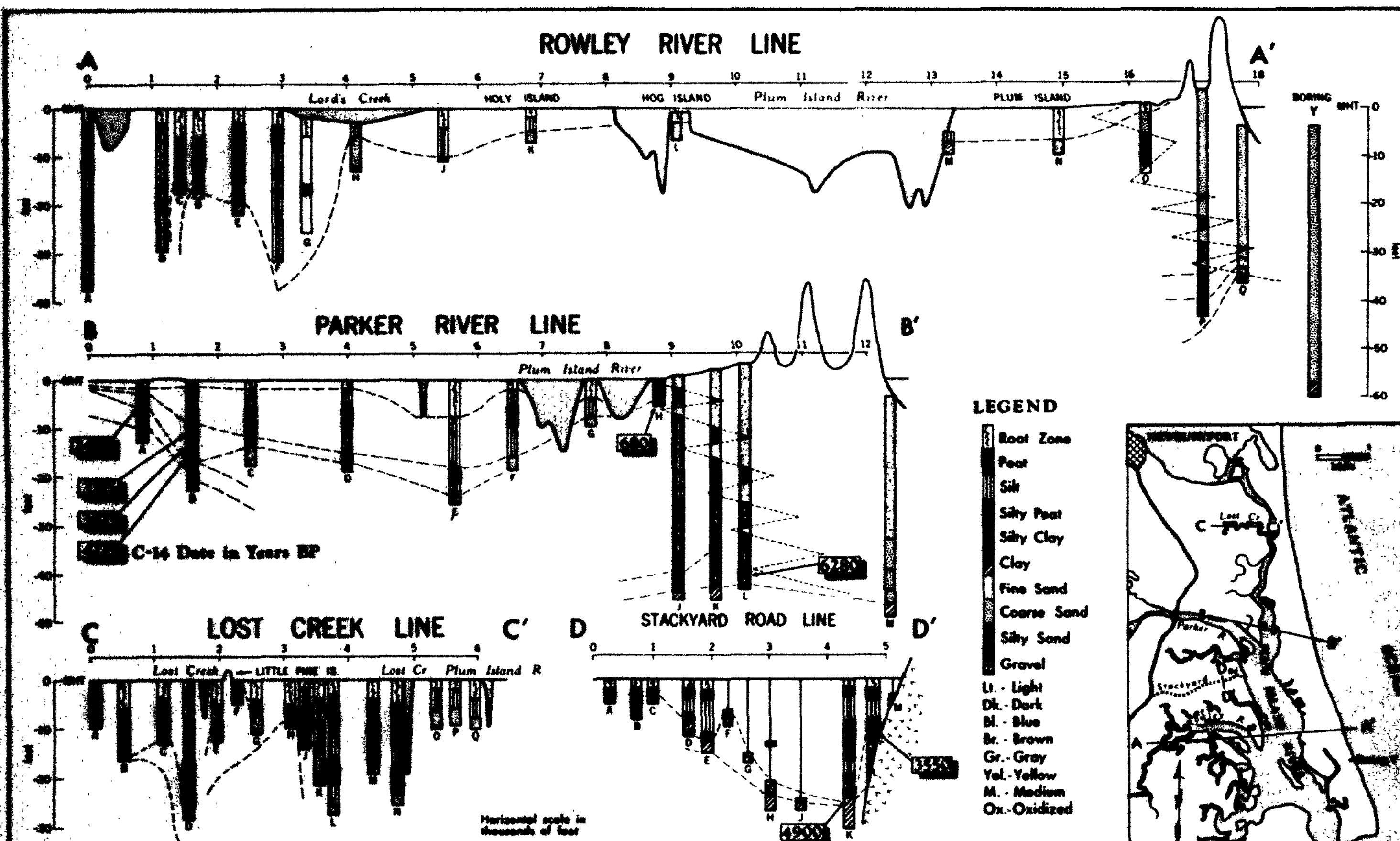


Fig. 6. Cross-sections of Plum Island marsh and beach established from borings. Inset map shows boring locations.

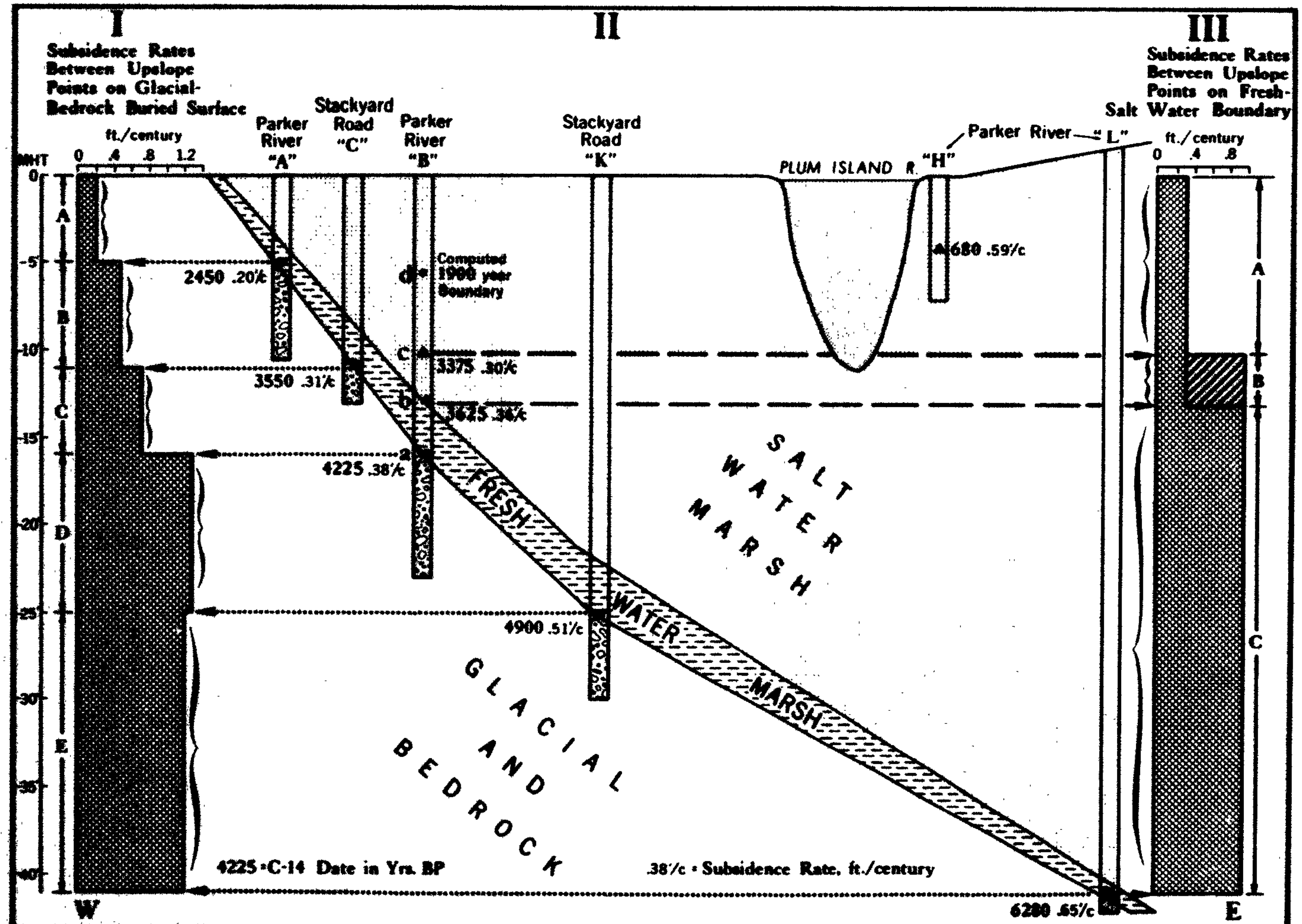


Fig. 7. Cross-section of Plum Island marsh correlated with radiocarbon dated peat. I. Indicates subsidence rates calculated on fresh marsh peat between upslope points. II. Shows marsh development rates calculated from position of dated peat to the surface. III. Portrays subsidence rates between the upslope fresh-salt water boundary.

basal peat in each boring below the present marsh datum is computed, a range from .65 feet per century for boring L to .20 feet per century for boring A is evident. The greatest rate of movement is indicated in the two deeper borings K and L, with lesser rates in the shallower and younger upslope samples. By computing rates of movement between adjacent upslope points along the glacial-bedrock and fresh marsh peat contact, decelerating rates of movement are shown. A striking change in rate between C and D, B and C, and again between A and B, occurs as is shown in the Figure 7-I.

The changes in rates should not be interpreted as marking positions of abrupt changes, but from them we can identify the time in the stratigraphic column when the termination of a more rapid period of subsidence occurred. The change probably began before 4000 years ago, and had terminated by at least 2500 years ago, as is indicated by the diminished rate to .20 of a foot per century for boring A. It could have resulted from a decrease in both eustatic rise of sea level and isostatic subsidence of land, or by the cessation of one and the continuance of the other. Both in time and depth, the zone that shows deceleration corresponds with an increase in accumulation of salt marsh peat. From the surface to approximately 12 feet, salt marsh peat and plant remains make up the major proportion of deposits, whereas, below this level the relative volume of plant remains is less, and clay, silt, and sand become dominant. Increased quantities of inorganic sediments reflect more open water conditions.

For specific data on sea level changes, the environmental boundaries of fresh-salt water dominance were established from the ecological assemblages, and these boundaries were radiocarbon dated. The boundary between fresh- and salt-water marsh is indicated by changes in sulphide content and in floral and faunal assemblages that occurred when the encroachment of high tides and saltwater replaced the fresh water environment. The significance of establishing and dating this environmental boundary was not fully appreciated while field work was in progress. As a result, only three borings, A, B and L, of the Parker River section furnished samples from which the boundary could be specifically determined from ecological assemblages, and only the boundary in B and L was radiocarbon dated. As the boundary for boring A was not dated, absolute time for sea level rise over this point is not known. Even though additional upslope fresh-salt water boundaries would be desirable, the importance of establishing the environmental change resulting from sea level rise is sufficiently demonstrated and could be refined with future study.

The fresh-salt water boundary of the Parker River borings (A, B, and L) show upslope positions of sea level rise from a depth of 41 feet to the surface. By using calculated rates of relative movement from the fresh-salt water boundary to the marsh surface for borings L and B"b", significant changes in rates are evident.

A rate of about .65 feet per century is calculated for boring L from the boundary to the surface, whereas in boring B the rate is reduced to .36 feet per century (Fig. 7-III). Since both boundaries lie close to the glacial-bedrock base, compaction within the Recent fresh marsh peat would not account for the great difference in rates, hence a change in process is suggested.

As we are dealing with established times and depths for sea level positions, the plotting of rates upslope between fresh-salt water boundary points is convincing in demonstrating a changing rate of movement (Fig. 7-II). The rate of sea level rise of the boundary between boring L and B"b" is 1.0 feet per century (Fig. 7-III-C), whereas, from the boundary at boring B"b" to the present marsh surface it is .36 feet per century (Fig. 7-III-A). If additional upslope environmental boundaries were established and dated, a more precise time and depth could be determined for the change in process. The 3625 years B.P. fresh-salt water boundary in boring B"b" appears to be close to the time when the process change culminated but is probably a few centuries too early. The reason for this assumption is that when the rate of marsh development (or sea level rise) is computed for the vertical distance between points L and B"c" the rate of 1.0 feet per century continues (Fig. 7-III-C). The continued rate to point B"c" is verified when sea level rise is computed for the vertical distance between points B"b" and B"c" which shows a rate slightly above 1.0 feet per century (Fig. 7-III-B). Rapid compaction of sediments probably accounts for the increased rate between B"b" and B"c". Since both dated samples come from marine environments, their differences in age and depth are in reality a measure of salt marsh growth or sea level rise and therefore are significant.

The position and rate of movement for point B"c" is interesting (Fig. 7-II, B"c"). It lies close to the position where the combined processes of land-sea movement terminated. Below this sample both sea rise and crustal downwarping produced faster rates of subsidence. Above this place in the boring a reduced speed of relative movement is interpreted to mark the cessation of noticeable amounts of eustatic sea level rise and the approximate initiation of the sea stillstand, where sea level has remained to the present with possible minor fluctuations. Relative changes of level above the stillstand boundary have resulted only, or at least predominantly, from crustal downwarping. Therefore, the 10 foot depth shown for this position in Figure 7-II B"c" represents the amount of crustal lowering during the past approximately 3375 years and establishes a rate of .30 of a foot per century for crustal lowering.

It is possible that .30 feet per century for land movement is slightly high since the point where reduction in rate of movement was not quite reached in the marine environment in boring B. However, the reduced rate of .20 feet per century for the basal peat in boring A is cogent evidence that the combined land-sea movement had ceased prior to this time. A more precise position of the eustatic stillstand is bracketed between point B"c" and the basal fresh marsh peat in boring A. For lack of additional control in the marine sediments above point B"c", the rate of .30 feet per century is here used for computing amounts of land movement, and the estimated time that the sea reached its present stillstand appears to have been 3000 years ago.

Studies made on peat accumulation in the Barnstable marshes show similar rates of growth to the Plum Island marsh. For the last 2100 years peat has shown an upward growth at a rate of approximately

.33 feet per century. Prior to 3700 years B.P. the rate of vertical growth was about 1.0 foot per century. Redfield and Rubin suggest that the sea stillstand was attained somewhere between 2100 and 3700 years B.P. and that relative sea level change during at least the last 2100 years is due primarily to land subsidence (p. 328, 1962).

The established position of the sea stillstand provided a base from which to measure and separate the amounts of crustal and sea movements above and below the boundary. Any movement along the glacial-bedrock slope after eustatic stillstand is the result of crustal downwarping. When considering the 41 foot depth for the Recent marsh deposits in Parker River boring L, 19.0 feet of the total depth is apparently the result of crustal downwarping, if we assume that the rate of crustal movement remained constant throughout the 6280 years B.P. The 19.0 feet was computed by using the .30 feet per century rate of movement established subsequent to the stillstand. The remaining 22.0 feet is then the result of eustatic sea level rise which would have occurred in the section below the 10 foot level in boring B prior to the time of the sea stillstand.

The reliability of the three radiocarbon dates in boring B is indicated by their mutual consistency. They appear to be compatible with other dates both below and above their positions along the valley slope. When considering rates of subsidence from the present surface to the three dated positions in boring B, a seemingly anomalous trend appears: the rates decrease from the bottom toward the surface instead of increasing, as would be expected. Crustal and/or eustatic movement appears to be great enough to conceal the effects of compaction, and the decrease in rates toward the surface suggest the cessation of sea level rise.

There is further evidence that coastal subsidence during the past approximate 2000 years is primarily the result of crustal lowering. At Kennebunk Beach, Maine, the boundary of the marine invasion which was established from floral and faunal studies, occurs at about the present mean high tide level (Fig. 2). Radiocarbon date of peat from the fresh-salt water boundary indicates that the sea reached its approximate present stand in this local area 1900 ± 105 years ago. Hence, sea level has remained practically unchanged for at least the past 1900 years at this location which lies north of Plum Island along the New England coast. Because of structural instability of coastal New England, the 1900 year date for marking the present sea stand in the Kennebunk area does not necessarily date the beginning of the stillstand, but it does indicate a minimum time for its duration.

The application of paleoecological studies to coastal investigations not only gives a more rational understanding of coastal processes in local areas but also provides data which has regional implications. From the floral and faunal studies the fresh-salt water boundary is established and it is this boundary that marks the position of high tide level. By following the boundary upslope to the present surface absolute control over positions of sea level rise is exercised. If several such oriented studies were made along a coast it would be possible to determine the effects of regional crustal movement.

When the 1900 year boundary line is extended south to boring B in Plum Island, it is computed to be 5.7 feet below the present salt marsh datum (Fig. 7-II, "d"). The 5.7 feet depth was determined from the .30 foot per century rate indicated for the 3375 year B.P. position in borings B"c" (Fig. 7-II, B"c"). The lower computed stratigraphic position of the 1900 boundary at Plum Island as compared to its position at Kennebunk Beach may reflect regional crustal movement.

The long eustatic stability of the Kennebunk Beach region may be evidence that structurally this area is near the axis between uplifting to the north and west and downdropping to the south and east. Near the Kennebunk Beach area morphological features change from more extensive sand beaches southward, to headlands with pocket beaches and cliffed coasts to the north. The distribution of clay shows a comparable pattern. From Kennebunk region north, the clay increases in distribution and rises to heights in excess of 300 feet above sea level, whereas, southward the clay decreases, both in distribution and elevation. At Boston the latest clay is approximately 30 feet above sea level. However, if the marine clays between Boston and Maine are of different ages the correlation of clay distribution with regional tilting would not be valid. The correlation is suggested to illustrate the possibility of determining regional structural trends from paleoecological studies. Additional data are necessary before final interpretations are possible.

Since bedrock of this region consists of consolidated Paleozoic rock, the differences in elevation of marine clay from Maine to Massachusetts suggests crustal warping. Lineaments that indicate a block pattern of movement for the over-all area are shown by the north-south direction of the coast line between Boston and Portland, and along the Kenebec and Penobscot Rivers which continue inland in a north-south direction from the coast. Northeast-southwest lineaments are indicated by the direction of the Connecticut and Rhode Island coast line and also the Maine coast northeast of Portland.

There is no evidence along the coast which would indicate any submergence above present high tidal level during Recent times. With a history of subsidence for the area, evidence for a higher than present Recent sea stand should be sought below present sea level. The paleoecologic profiles showed that no erosional surfaces or weathered zones were present in the subsurface, nor were there reversals in floral and faunal assemblages that would indicate a switch in environments from salt to fresh water. The record shows persistent subsidence of the coast from at least 6300 years ago to the present. The combined effect of eustatic and isostatic movements caused more rapid changes from 6300 to about 3000 years ago. Eustatic stillstand was reached approximately 3000 years ago, but crustal downwarping has continued to the present at a rate of about .30 feet per century.

<u>Local Compaction of Sediments</u>

Compaction of sediments has not been an important consideration in any of the above discussion because most of the data considered have come from along the upslope glacial-bedrock boundary. However, some of the movement rates and radiocarbon dates lie within the wedge of Recent sediments where compaction has certainly affected their vertical positions. Although no attempt is made to make a detailed study of compaction and/or the engineering properties of the sediments a general discussion of the problem is warranted, and in the ensuing section a method is demonstrated whereby approximate amounts of compaction can be determined.

It is recognized that compaction rates vary with sediment type, amount of overburden, and time. The consolidation of soils has been intensely studied by foundation engineers since Terzaghi in 1923 introduced the field of soil mechanics (Terzaghi, 1943). However, few studies have been made on measuring compaction as a normal process in Recent sediment without reference to effects of man's induced overburden. Hamilton's recent article on "Consolidation and Lithification of Deep-Sea Sediments," summarizes the principles involved as applied to ocean bottom sediments (Hamilton, 1959) and in general these principles also apply to unconsolidated Recent sediments of Plum Island marsh, but on a reduced scale. With a given type of sediment, Hamilton has shown that the relationship between depth in sediment and cumulative pressure is inversely proportional to void ratio and percentage of porosity (Hamilton, p. 1404). Therefore, the rates of greatest compaction will decrease with depth as cumulative pressure increases and void ratios decrease. Because of differing relationships between sediment type, hydrostatic uplift, amount of time, and overburden, the compaction rate with depth does not necessarily decrease at a uniform rate.

Basis for separating the amount of compaction from land-sea changes of level also involves duration of the eustatic stillstand. The previously determined .30 feet per century rate for land lowering after the eustatic stillstand was attained is used to compute the approximate amount of compaction. Within the Recent deposits selected control points provide data which make possible an estimate for compaction in a generalized way. Although additional control points are desirable, the procedure is demonstrated by the use of the radiocarbon date at the base of boring L (Fig. 5-B) as one major control, and boring H as the second. A maximum amount of compaction for the Plum Island Recent sediments is determined from boring H (Fig. 7) which is located over the thickest section of Recent sediments where greatest compaction is expected. Total compaction effects are not shown in boring H because the sample was taken at a 4 foot depth below the surface to insure a radiocarbon date old enough to be reliable. The difference between the total subsidence rate of .59 feet per century for boring H and .30 feet per century (post-stillstand rate for crustal lowering) is the result of compaction. The rate of compaction at the 4 foot depth in boring H is then .29 feet per century which indicates that approximately 2 feet out of the total depth of 4 feet is the result of compaction. Figure 5-B is an extrapolation showing the amount of compaction with depth as based on the calculated 2 feet of compaction for boring H. Compaction rates decrease from the surface to negligible amounts along the upslope glacial-bedrock surface. An approximate amount for a given depth is ascertained from Figure 5-B along the line extended between boring H and L (Fig. 7). Because of the different relationship between sediment type, hydrostatic uplift, and amount of overburden, a decrease in compaction with depth does not follow a straight line as closely as implied in Figure 5-B, but an approximate allowance for compaction in the Recent deposits is well worth considering.

Since boring H is located over the thickest section of marsh deposits, any line on Figure 5-B extended from boring H to other upslope positions along the glacial-bedrock surface would exaggerate compaction effects toward shallower depths. For this reason near-surface control points are necessary over any vertical section where compaction data is sought. No attempt was made during fieldwork to determine compaction rates in shallow marsh deposits, but they can be calculated approximately from data such as exist for boring B.

It is interesting to compare total subsidence rates shown for boring H and L in Figure 7-II. Even though there is only .06 feet per century difference, boring H represents the combined amounts of crustal lowering and compaction, whereas boring L includes the effects of eustatic sea level rise and crustal lowering.

## Summary of Relative Sea Level Changes

A summation of results derived from paleoecologic studies and radiocarbon dating as related to sea level changes is shown in Figure 8. Since control over the amount of relative land-sea movement is restricted to the past 6300 years, changes prior to that time are estimated and the first three diagrams (Fig. 8, 1, 2, and 3) are hypothetical. In the remaining sketches (4 - 8) the relative positions of land and sea are determined from the borings and radiocarbon dates discussed earlier. The direction and amounts of land and sea movement for the past 6300 years are differentiated on a factual basis.

The present mean high tide in the Plum Island area is the datum on which the sketches in Figure 8 are based. The datum is indicated by a dashed line on each diagram and its position shows the relative differences in elevation between land and sea at the time specified. The position of the vertical scale is the same on all the graphs in Figure 8 except 1 and 2, where the datum was raised to higher levels in order to indicate the magnitude of land subsidence caused by the ice load. The Pine Swamp Road Bog (Fig. 9) is diagramatically indicated on the sketches and its vertical position in reference to the datum is implied. Since the marine clay and the Pine Swamp Road bog are respectively 20 and 40 feet above the present mean high tide datum (Fig. 8-8) their relative positions remain constant throughout Figure 8. The land position was determined from data compiled on Figure 7 and by applying a crustal downwarping factor of .30 feet per century (the rate of isostatic movement after eustatic stillstand) to each of the points depicted. The difference between the calculated amount of land subsidence and the total depth of the boring to the glacial-bedrock boundary is the basis for eustatic change in sea level positions. Marine clay position is one of the major clues for interpreting the events of land-sea changes and on the diagrams in Figure 8 the known positions of the sea are correlated with the height of the clay above the present datum.

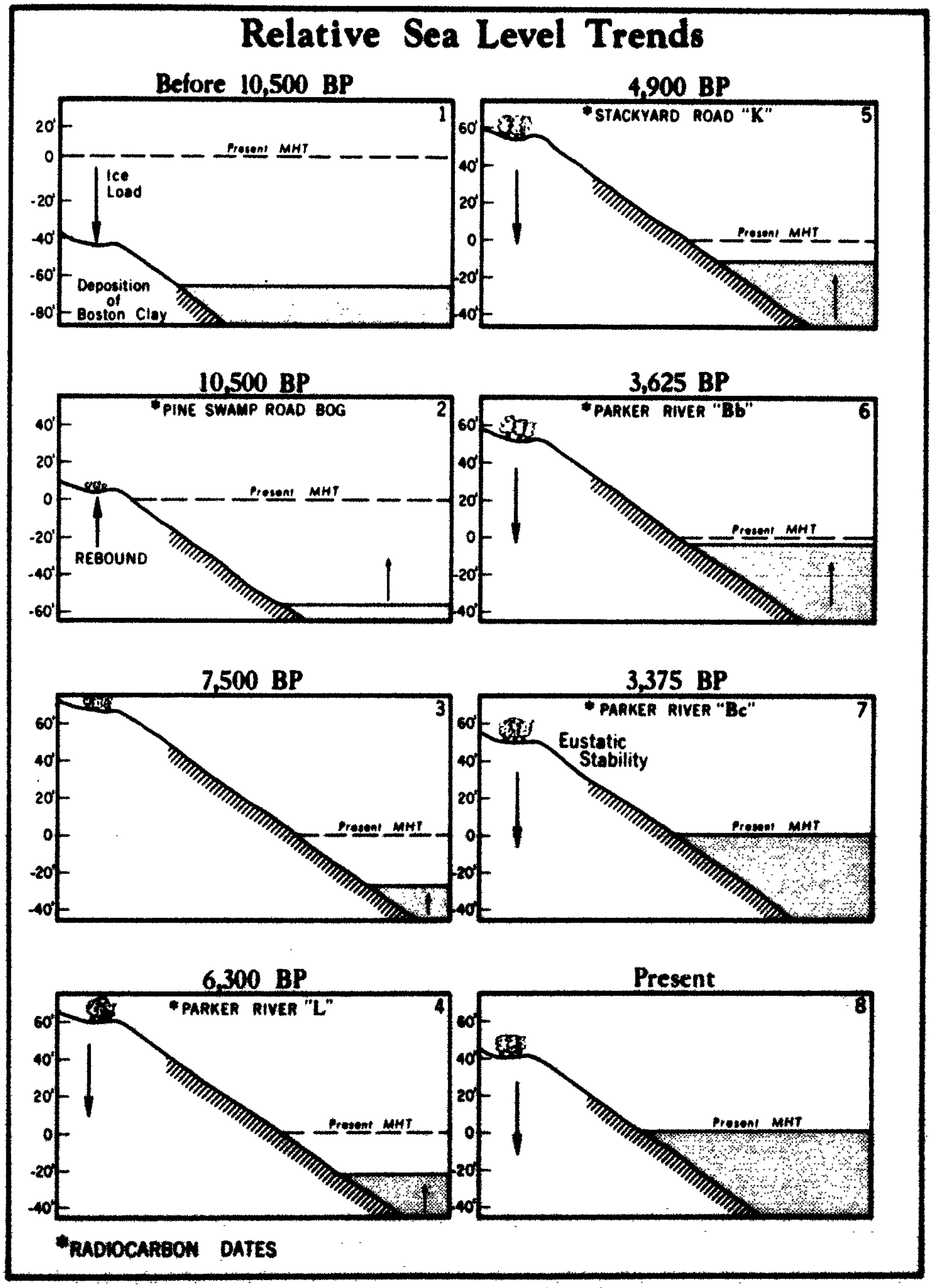


Fig. 8. Schematic diagrams to indicate relative changes of level for the past 11,000 years as related to the present and mean high tide datum. The position of the datum in numbers 1-3 is estimated. Numbers 4-8 are based upon the position and age of peats in the coastal marsh.

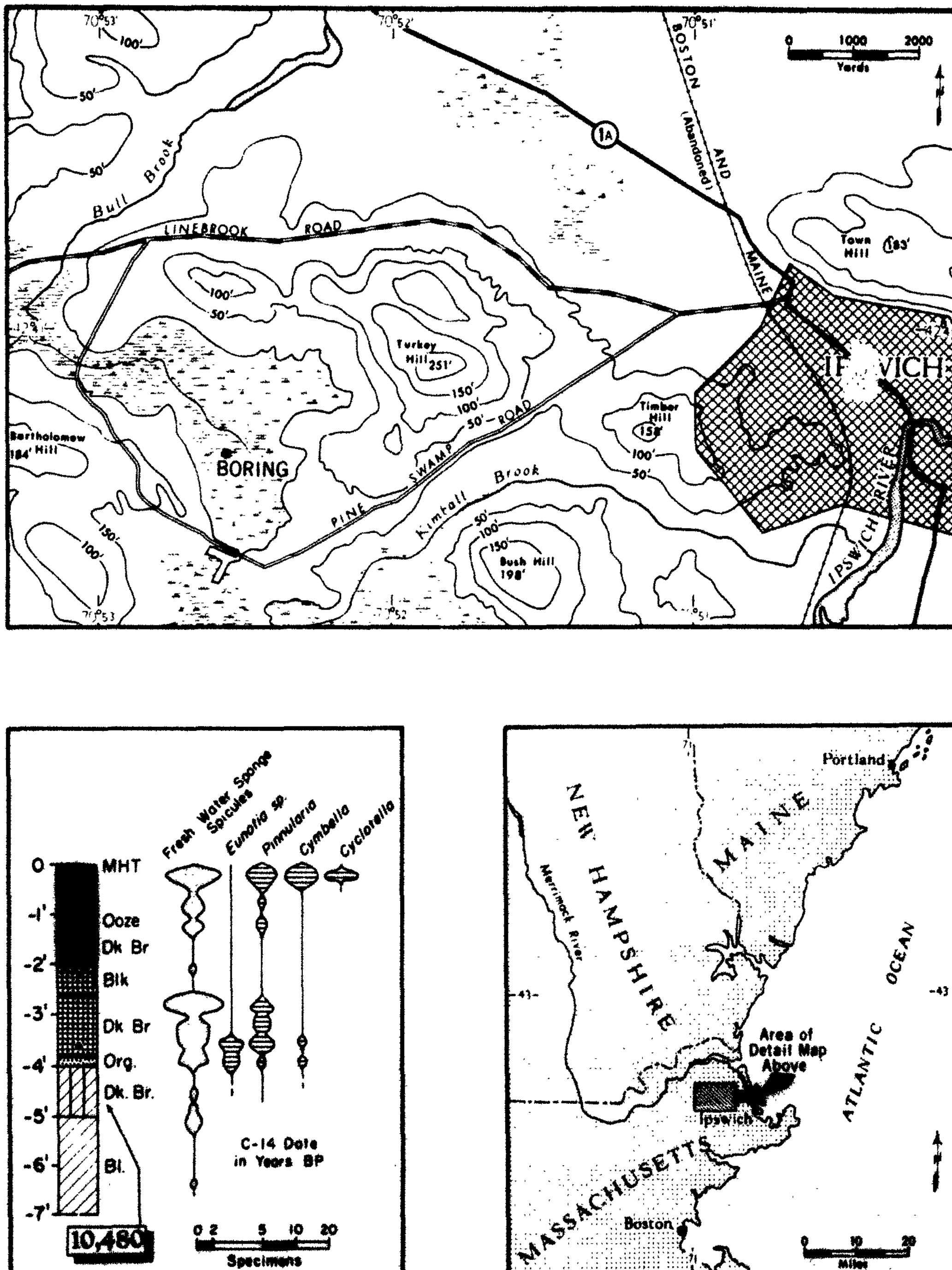


Fig. 9. Pine Swamp Road boring location, section and diatom spectrum. Absence of diatoms in the peat section between 1.5 and 2.5 feet indicates a dryer phase in the bog.

Before 10,500 years B.P. (Figure 8-1): Marine clay was deposited during closing stages of the last glacial period in an estuarine area at or near sea level. These readily recognizable sediments provide a base for measurement of subsequent relative movements of land and sea. At the time the clay was deposited, both land and sea were lower in elevation than they are at present. Ice load had depressed the land an unknown amount, therefore the 70 feet of land subsidence below the present mean high tide datum indicated on the sketch is simply an estimate.

By 10,500 years B.P. (Fig. 8-2): Following ice retreat the land rebounded more rapidly than sea level rose. This is clearly indicated by the presence of glaciomarine clay above high tide level and its oxidized surface beneath Plum Island marsh. The land-sea relationship is estimated, but a radiocarbon date on peat from the bog (Fig. 9) gives indirect evidence on the general trend of relative movement. A 4-foot peat section in the Pine Swamp Road bog was analysed for floral and faunal content.* The presence or absence of diatoms showed a correlation with peat types in the section which reveal clues to environmental conditions during the bog development. The bog surface is approximately 40 feet above the sea datum and is drained by a small tributary into Bull Brook (Fig. 9). The peat section directly overlies glacial deposits and varies from the surface to the bottom from a 1.5-foot layer of black ooze peat, a 6-inch layer of brown peat, a 6-inch layer of black peat, and 1.5 feet of brown peat at the bottom. The lower, brown peat with fresh water diatoms represents an acquatic habitat of fresh water. The middle, black forest peat with no diatoms represents a more terrestrial condition in the bog. In the black, ooze peat which overlies the forest peat are fresh water diatoms which indicates a reversion to an aquatic swamp environment. Climatic influences are commonly appealed to in explaining such habitat changes, but it appears that local environmental conditions are more important. By impeding or improving drainage of local areas plant succession can be reversed or advanced. At the time the lower brown peat was forming the bog surface was nearer sea level than at present and drainage was poor. With the gradual uplift of the land, and a filling in of the bog with vegetal accumulation drainage conditions were improved and plant succession changed to more terrestrial types. The return toward an equatic environment following the formation of black forest peat could have resulted from the reversal of land movement from rebound to crustal lowering, or from the influence of man. The construction of a reservoir downstream from the Pine Swamp Road bog is more likely the cause of the area's return to pond and swamp conditions. Since no radiocarbon dates are associated with the ecological changes in the bog, the time of their occurrence is unknown. Because of the antiquity of the 10,500 years B.P. date for the basal peat, the initial deposits in the bog indicate a time not far behind the ice retreat and the continuation of crustal rebound. The proximity of the bog to sea level is indicated by marine clay which is only 20 feet below the bog in elevation.

*Dr. Ulrich Jux, Paleoecologist, Geology Department, University of Cologne, analysed the Peat Section for floral and faunal content.

By 7500 years B.P. (Fig. 8-3): The relationship between land and sea positions by 7500 years B.P. are only educated guesses. Somewhere between 10,500 and 6300 years ago a maximum amount of land uplift was reached and the reversal of movement toward subsidence had occurred. The 7500 B.P. is an estimate of the time that the land reversed its movement and therefore had reached its maximum elevation. The height of about 65 feet above the datum shown on the sketch was calculated from the amount of crustal movement determined for the 6300 years B.P. date in the 41 foot Parker River L boring.

Between 6300 and 3375 years B.P. (Fig. 8-4 to 7): The diagrams that represent periods for the past 6300 years are based on more absolute data. Amounts of sea level rise and crustal subsidence were determined for each boring. From these data a plot of the relative sea and land level positions was possible.

The sea 6300 years ago was 22 feet below the present datum and was rising at a rate of approximately .70 feet per century. The land surface was about 19 feet higher than it is presently and sinking at a rate of .30 feet per century which is assumed to be constant thoughout this period.

By 4900 years ago the sea had risen to 11 feet below present datum and the land had lowered 5 feet from its 6300 years B.P. position. By 3625 years ago the sea had risen to approximately 3 feet below the datum and the land had subsided an additional 4 feet from its previously established position.

The termination of sea level rise at approximately 3000 years ago is indicated in sketch 7. By this time the land had lowered another 3 feet and from this position to the present a continuing land subsidence has resulted in coastal drowning.

Present (Fig. 8-8): During the past 3000 years the sea has been relatively stable but the land has continued to sink and since eustatic stillstand the crust has lowered 10 feet. The diagrams show a gradual eustatic rise of about 22 feet between 6300 and 3000 years ago when the sea reached its stillstand. In the past 6300 years the land has subsided about 19 feet and crustal downwarping continues at an approximate rate of .30 feet per century along the Plum Island coast.

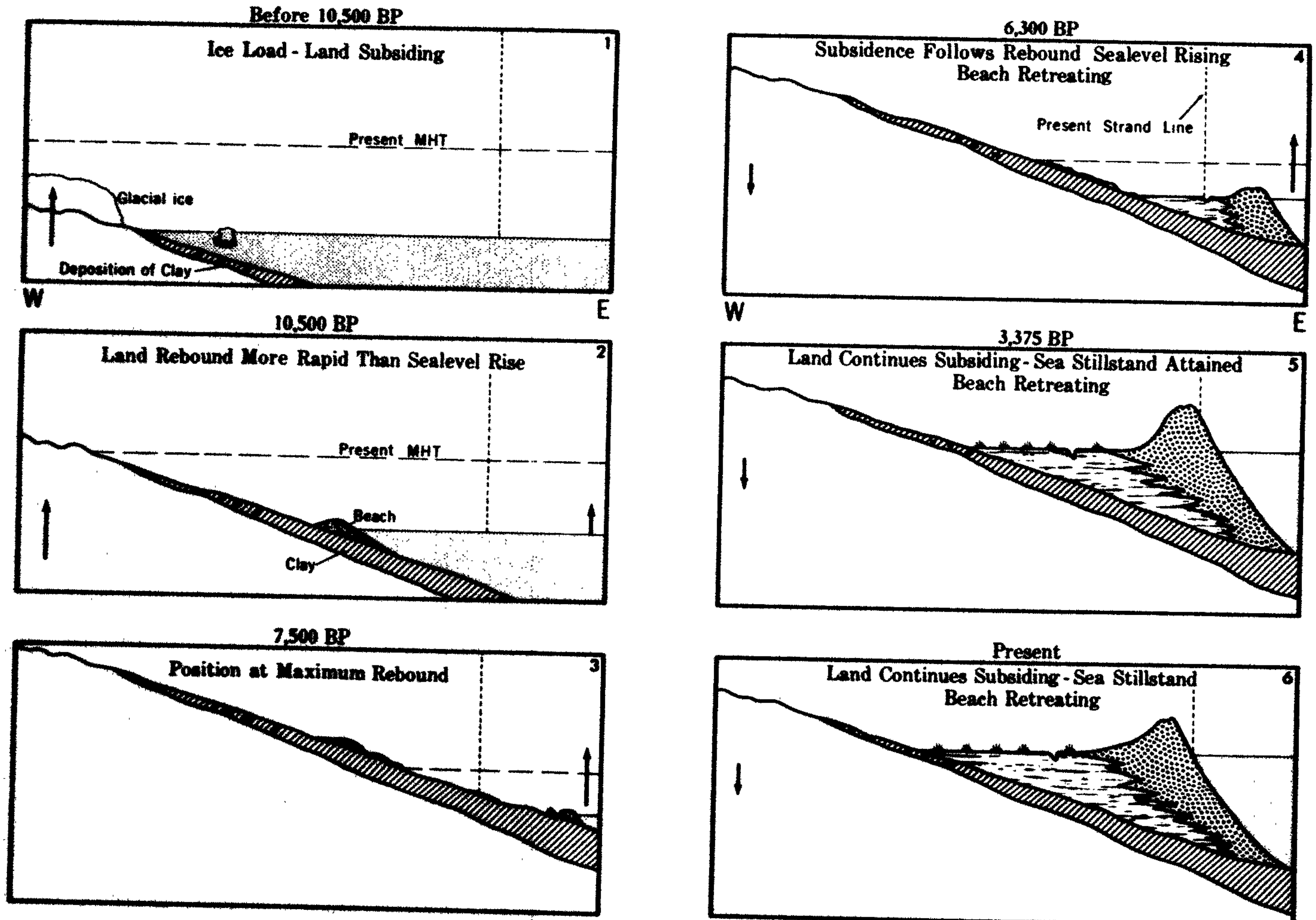


**Fig. 10. Plum Island strandline changes and beach development is correlated with relative changes of level for the past 11,000 years. Direction of strandline displacement is shown by the position of the vertical dashed line.**

## ORIGIN AND DEVELOPMENT OF PLUM ISLAND

Plum Island and other beaches presently fronting the coast between Kennebunk Beach and Cape Ann are Recent features. Their distribution is directly related to coastal areas where Quaternary glacial deposits are present. Relative changes of level during the past 11,000 years have affected the position of the shoreline and altered the source of sediments. The development of Plum Island began sometime prior to 6300 years ago. At the time of origin the sea was lower than it is presently and the land was higher in elevation. The present single-crested beach and dunal development is the result of a transgressive sea eroding, reworking and depositing Quaternary sediments along an unstable coast.

### Correlation: Shoreline with Relative Changes of Level

The relative changes of level during the past11,000 years have affected the shoreline along a relatively narrow zone parallel to the present strandline. Glaciomarine clay inland from Plum Island is evidence that the shoreline during clay deposition lay westward of its present position (Fig. 10). Inland, the clay grades both laterally and vertically into glaciofluvial outwash deposits of sands and gravels (Sammel, U. S. Geological Survey, Boston, Mass., oral communication, 1960). The outwash material is considered to be ice-contact deposits which would place the ice front in the proximity of Plum Island during clay deposition. The higher sea stand indicated by the marine clay elevation indicates the relative changes of level between land and sea that have occurred since clay deposition. Actually, during the period of clay formation both land and sea were lower in elevation than they are presently (Fig. 10-1). A schematic relationship between the marine clay shoreline and present shoreline is illustrated by comparing diagram 1 with diagram 6 (Fig. 10).

With ice retreat, coastal upwarping progressed at a more rapid rate than sea level rise, which resulted in shoreline displacement seaward from its present position. However, simultaneous sea level rise voided part of the effects of land upwarping and the amount of shoreline displacement was reduced (Fig. 10-2,3). Subsequently, with land subsidence and sea level rise occurring simultaneously, the opposing movements reduced the net effect of shoreline migration (Fig. 10-4 to 6). It appears that sometime before 6300 years B.P. and the time of the sea stillstand, sea level was rising at a faster rate than the land was lowering. During the period of coastal drowning retrogression of the strandline would occur if sufficient sediments were not added to the beach front to maintain its seaward position. Following the sea stillstand about 3000 years ago (Fig. 10-5) the effect of land subsidence continued coastal drowning but at a reduced rate. Since the stillstand, a gradual retrogression of the shoreline has occurred to the present.

Evidence for shoreline retreat is indicated by the near-shore residual boulders from a former drumlin (Fig. 4), the sea cliff on the existing drumlin on the south end of the island, and erosion of the foredune face by storm waves. In addition, borings through Plum Island indicate a westward migration of the Island during at least the last 6300 years. However, the rate of retrogression of the shoreline is not great. Comparison of maps and surveys for the past approximate 100 years indicates only a slight amount of shoreline retreat along the southeastern coast of Plum Island. Northward to the Merrimack River mouth local areas of coastal accretion and retreat occur but no definite overall change is shown.

Correlation: Relative Changes of Level and Beach Development

In the Plum Island area no evidence of former higher standing beaches were observed. During glaciomarine clay deposition it is unlikely that beaches were extensively developed along a shoreline dominated by ice and glaciofluvial deposits. If beaches existed they were probably transient and restricted to local areas. Subsequent glaciofluvial outwash and erosion have probably obliterated any evidence of former beaches.

Beaches likely formed along the coast during the time of land rebound and sea level rise but no evidence for their existence remains. Much of the zone where such evidence would be has subsequently been drowned by relative transgression of the sea. Any evidence for above-sea level beaches would be restricted to the marine clay zone but if they existed they have since been destroyed by erosion. It is reasonable to assume that beaches would form as soon as waves and currents could attack the shore zone once it was freed from ice.

Since beaches are a time transgressive feature, evolution of Plum Island began with the first beach which formed following glacial retreat. However, an emerging shoreline during the early part of Recent times would strand successive beach material (Fig. 10-2). Hence the position of the initial beaches had little relevance to the location of the present Plum Island Beach. It was not until the end of coastal uplift that the position of the beach had a direct linkage with the present. At this time the beach lay seaward from the present strandline and below present sea level (Fig. 10-3). The time estimated for the culmination of coastal uplift is 7500 years ago. From this approximate time forward to the present the beach has progressively retrograded as the sea transgressed. Through time, the beach has maintained its general upslope relationship with underlying glacial deposits and sea level. Because of coastal subsidence basal wave erosion rising against the foreshore sea floor has caused shoreline retreat (Fig. 10, 3-6). Sufficient sediments were not available locally to maintain a stable shoreline. Therefore continued lowering of the land without shoreline retreat would progressively thicken the sand section beneath the beach. This does not appear to have occurred.

Rates of beach development and shoreline change since coastal drowning began have varied. Initially, with sea level rising eustatically, contemporaneously with land subsidence, the combined movements in opposite directions increased the speed of drowning (Fig. 10-3 to -5). The sea stillstand approximately 3000 years ago slowed the rate of coastal drowning and beach change has been less spectacular.

Borings along the Rowley River and Parker River lines (Fig. 6) through the beaches and dunes reveals a wedge of sand which is wider at the surface than it is at the bottom. The shape of the wedge suggests a beach and dune complex transgressing westward over the adjacent marsh. Reworked sand which resembles present beach sands in sorting and grain-size directly overlay clay in borings M and Q of the Parker and Rowley River lines respectively. These two borings were made through the present beach fronts at approximately mid-tide position. Sand with broken shell extended throughout the boring and no organic plant remains were present. Borings through the dunes and the sand apron westward from the main dunal belt (Parker River J, K, and L; Rowley River O and P) showed layers of sand intercalated with layers of organic plant remains which were intermixed with sand. When plotted in cross-section the layers where plant remains are present extends farther seaward toward the bottom and landward toward the top. This pattern reveals the encroachment of beach and dunal sand westward over adjacent marsh. The presence of fresh marsh peat at the base of boring L, Parker River line shows that a protective beach lay seaward of this position (Fig. 10-4). The 6280 year B.P. age for the basal peat gives a minimum of time for beach development along this section of the coast. Organic plant remains above the basal peat are all from salt marsh plants. These reflect the amount of plant accumulation which is correlated with sea level rise since its invasion over the basal peat in boring L. Boring H (Parker River line) extends through the westward extension of dunal sand which is presently burying adjacent salt marsh. The dunal sand overlies a compact layer of salt marsh peat. There is little sand content in the bottom zone of the peat but sand increases in quantity toward the surface where it blends with surface wind-drifted sand. A radiocarbon date of 680 years B.P. indicates the recency of the encroaching dunal sand over the marsh.

The horizontal distance between boring L and H is approximately 1500 feet and an approximate rate for the westward shifting of sand is indicated when the radiocarbon dates for boring L and H are compared with the horizontal distance which separates the borings. Whether or not there is a correlation between the westward movement of dunal sand and coastal retreat is not certain but there appears to be a connection.

Evidence shown on Figure 6 reveals the time-depth development of Plum Island and indicates that Plum Island beach was in existence prior to 6280 years B.P. The location of the initial beach which established the position and alignment of the present beach is below sea level, but its original seaward position is indicated when the borings through Plum Island are correlated with the relative changes of level.

## Correlation: Relative Changes of Level and Sediment Supply

The characteristics of the single-crested beach of Plum Island are directly correlated with source of sediments, sea processes, and relative changes of level. Retrogression of the shoreline is evidence that sediment supply to the beach front has not kept pace with coastal retreat, erosion of the foredune face by storms, and less dunal development than occurred formerly indicates a gradual loss of sand through time. With ice retreat, initially there would be a greater source of glacial sediments available for beach construction. Through time, depletion of sediment directly relates to the continuing processes of erosion, decreased sedimentation and relative changes of level. During the period of land emergence beach material was probably stranded above the reach of the waves (Fig. 10-3). As the sea eventually transgressed over this surface wave processes reworked some of the formerly stranded deposits into beaches. Coastal drowning for at least the past 6300 years has probably resulted in a gradual loss of sediments. Sand supplies today are small in comparison with amounts initially available following ice retreat. Coastal drowning occurred at a more rapid rate prior to the sea stillstand. Following the stillstand land subsidence continues at a slower rate, but has a long term effect on sediment supply on Plum Island beach.

In addition to the effects of time and relative changes of level littoral currents have added sand to the down-drift area of Plum Island. Littoral currents have transported sand from north to south between Great Boars Head and Cape Ann. The source of sand is from the sea floor, the Merrimack River, and coastal erosion northward to Great Boars Head. Cape Ann traps the sand in the down-drift area and there are extensive accumulations offshore. Source of sand for the extensive dunal development on Plum Island, Castle Neck and Coffin Beach is largely attributed to the littoral current. Onshore easterly winds have transported quantities of sand westward so that the dune belt is over 500 yards wide in places and some individual dunes attain elevations of over 30 feet. Apparently the down-coast drift of sand is a slow but persistent process. No multiple accretion ridges have developed which if present would indicate a prograding shoreline. Nor has there been enough sand added to offset slow retrogression of the Plum Island beach. Sediment which apparently comes from the Merrimack River is maintaining a near-stable strandline along the northern section of Plum Island. Southward the strandline is retrograding slowly.

## Summary of the Origin and Development of Plum Island

The single-crested beach of Plum Island is a time-transgressive feature. It originated in early Recent times when sea level was lower and the strandline was seaward of its present position. Although earlier beaches probably existed, the beach which fronted the Plum Island basin at the time the land began to subside, has direct process-ties with the present. From this time forward progressive drowning of the coast has resulted in the gradual retrogression of the shoreline to its present position. From 6280 years B.P. to the time of the stillstand, coastal drowning was occurring at a more rapid rate than it has since stillstand. Prior to the stillstand eustatic sea level rise likely progressed more rapidly than crustal lowering. During the period of coastal drowning and beach retreat wave erosion has maintained an equilibrium with the near-shore sea floor as the strandline moved upslope. Through this process, the base of the beach and the underlying blue clay on which the beach is anchored have maintained a more or less uniform relationship to sea level. Therefore the origin, position and alignment of Plum Island was established at least 6300 years ago. The salt marsh flats and estuarine tidal channels which superficially separate the beach from the mainland conceal the real reason for its location. The remaining beaches in the survey area have histories similar to Plum Island. The valleys they front are smaller and the relationship between the land and sea is more easily discernible.

## SELECTED BIBLIOGRAPHY


Barghorn, Elso S., et al,
1949, The Boylston Street Fishweir II, Papers of the Robert S. Peabody Foundation for Archaeology, V. 4, No. 1, 133 pp.

Barghorn, Elso S.,
1953, "Recent Changes in Sea Level Along the New England Coast: New Archaeological Evidence," Science, V. 117, p. 597-598.

Bennema, J.
1954, "Holocene Movements of Land and Sea-level in the Coastal Area of the Netherlenad," Geol. en Mijnb., N.S. 16, pp. 254-264.

Blomm, Arthur L.,
1960, "Late Pleistocene Changes of Sealevel in Southwestern Maine," Maine Geol. Survey.

Byrne, J. V., LeRoy, O. and Riley, C. M.,
1959, "The Chenier Plain and its Stratigraphy, Southwestern Louisiana," Gulf Coast Assoc. Geol. Socs. Trans., V. 9, pp. 1-23.

Chute, N. E., and Nichols, R. L.,
1941, "The Geology of the Coast of Northeastern Massachusetts," Mass. Dept. Public Works and U. S. Geol. Survey Cooperative Geology Project, Bull. 7, 48 pp.

Fisk, H. N.,
1952, Geological Investigation of the Atchafalaya Basin and the Problem of Mississippi River Diversion, U. S. Army Corps of Engineers, Waterways Expt. Sta., Miss, River Comm., V. 2, 145 pp.

Fisk, H. N. and McFarlan, E., Jr.,
1955, "Late Quaternary Deposits of the Mississippi River," G.S.A., Special Paper, V. 62, pp. 279-302.

Flint, R. F.,
1953, "Probable Wisconsin Substages and Late-Wisconsin Events in Northeastern United States and Southeastern Canada," G.S.A. Bull., V. 64, pp. 897-919.

Godwin, H., Suggate, R. P., and Willis, E. H.,
1958, "Radiocarbon Dating of the Last Rise in Ocean-level," Nature, V. 181, pp. 1518-1519.

Gould, H. R., and McFarlan, E., Jr.,
1959, "Geologic History of the Chenier Plain, Southwestern Louisiana," Gulf Coast Assoc. Geol Socs. Trans., V. 9, pp. 237-260.

Hamilton, Edwin L.,
1959, "Thickness and Consolidation of Deep-Sea Sediments," G.S.A. Bull., V. 70, pp. 1399-1424.

Johnson, F., et al.,
1942, The Boylston Street Fishweir, Papers of the Robert S. Peabody Foundation for Archaeology, V. 2, 212 pp.

Judson, Sheldon, et al.,
1949, The Boylston Street Fishweir II, Papers of the Robert S. Peabody Foundation for Archaeology, V. 4, 133 pp.

Kaye, C. A.,
1961, "Pleistocene Stratigraphy of Boston, Massachusetts," Geol. Survey Prof. Paper 424-B, No. 34, pp. B-73.

LeBlanc, Rufus J. and Bernard, Hugh A.,
1954, "Résumé of Late Recent Geological History of the Gulf Coast," Geol. en Mijnb, (N.W. Ser.), 16e Jaargang, pp. 185-194.

Marmer, H. A.,
1951, "Tidal Datum Planes," U.S. Dept. of Commerce, Coast and Geodetic Survey Special Pub. 135, 142 pp.

McFarlan, E. Jr.,
1960, "Radiocarbon Dating of Late Quaternary Deposits, South Louisiana," G.S.A. Bull., V. 72, pp. 129-158.

Newman, Walter S. and Fairbridge, Rhodes W.,
1961, "Postglacial Crustal Subsidence of Coastal New England," Program G.S.A. (Abstracts) Annual Meetings, p. 115A.

Nichols, R. L.,
1942, "Shoreline Changes on Plum Island, Massachusetts," Am. Jr. Sci., V. 240, pp. 349-355.

Oldale, Robert N.,
1961, "Late-Glacial Marine Deposits in the Salem Quadrangle, Massachusetts," Geol. Survey Prof. Paper 424-C, No. 171, pp. C-59.

Redfield, Alfred C. and Rubin, Meyer,
1962, "Age of Salt Marsh Peat in Relation to Recent Changes in Sea Level," Science, V. 117, p. 328.

Russell, Richard J.,
1957, "Instability of Sea Level," Am. Scientist, V. 45, pp. 414-430.

Russell, Richard J.,
1958, "Long Straight Beaches," Eclogae Geologicae Helvetiae, V. 51, pp. 591-598.

Terzaghi, K.,
1943, Theoretical Soil Mechanics, N. Y.: Wiley, 510 pp.

Tuttle, S. D.,
1952, "The Quaternary Geology of the Coastal Region of New Hampshire," Unpublished Ph.D. Thesis, Harvard Univ. Lib., 186 pp.

1960, "Evolution of the New Hampshire Shore Line," G.S.A. Bull., V. 71, pp. 1211-1222.

U.S. Army Corps of Engineers,
1941, Interim Report on Continuing Beach Erosion Study at Salisbury Beach, Massachusetts, Office of the Div. Engineer, New England Div., Boston, Mass., 16 pp.

U. S. Army Corps of Engineers,
1953, Beach Erosion Control Report on Cooperative Study of Hampton Beach, New Hampshire, Office of the Div. Eng., New England Div., Boston, Mass., 27 pp.

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